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UPDATE AND IMPROVEMENT OF THE CONTROL COST SEGMENT OF THE IMPLEMENTATION PLANNING PROGRAM

F. L. Bellegia, et al

Research Triangle Institution

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U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
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Most point source emitters of sulfur dioxide and particulate matter are identified and assigned a four-digit Standard Industrial Classification (SIC) Code and a two-digit process code. The latter specifically identifies the process taking place within the SIC. Particulate matter and sulfur dioxide control equipment applicable to each SIC-process code combination are identified, and typical removal efficiencies reported. Tandem control arrangements are also considered. Algorithms are developed for estimating the costs associated with installing and operating the control equipment identified as applicable to the SIC-process code combinations.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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by

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ii

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UPDATE OF CONTROL COST SEGMENT OF THE

IMPLEMENTATION PLANNING PROGRAM

CONTENTS

		Page
LIST OF FIGURES		v
LIST OF TABLES		vi
1.0	INTRODUCTION	1
2.0	REDEFINITION OF SIC-PROCESS CODES	3
	2.1 REFERENCES	4
3.0	DEVICE MATRIX	19
4.0	COMBINED EFFICIENCY OF TWO PARTICULATE CONTROL UNITS IN TANDEM	41
	4.1 EMPIRICAL CORRECTION FACTOR METHOD	41
	4.2 OVERALL EFFICIENCY BY ANALYTICAL METHOD	47
	4.3 TANDEM EFFICIENCY ALGORITHMS - COMPARISON	52
	4.4 CALCULATION FROM EXPERIMENTAL DATA	53
	4.4.1 Graphical Method	53
	4.4.2 Approximate Model	62
	4.4.3 Analytical Method	64
5.0	DEVICE EFFICIENCY	68
	5.1 MECHANICAL DEVICES - EFFICIENCY	68
	5.2 ELECTROSTATIC PRECIPITATORS - EFFICIENCY	69
	5.3 ADD-ON DEVICE EFFICIENCY	72
6.0	IMPLEMENTATION PLANNING PROGRAM PARTICULATE CONTROL SYSTEM COSTS	73
	6.1 DISCUSSION AND BASIS FOR EQUATIONS	73
	6.1.1 Capital Costs	73
	6.1.2 Annual Operating and Maintenance Expenses	76
	6.1.3 Annualized Capital Costs	84
	6.2 CAPITAL COST EQUATIONS - PARTICULATE CONTROL SYSTEMS	87
	6.3 ANNUAL OPERATING COST EQUATIONS - PARTICULATE CONTROL SYSTEMS	89
	6.4 ANNUALIZED CAPITAL COSTS EQUATION - PARTICULATE CONTROL SYSTEMS	92
	6.5 PRINCIPAL DATA SOURCES USED IN DEVELOPING PARTICULATE CAPITAL AND OPERATING COST EQUATIONS	94
7.0	SULFUR DIOXIDE CONTROL SYSTEM COSTS	94
	7.1 DISCUSSION	94
	7.1.1 Selection of the SO_2 Control System	97
	7.1.2 Wet Gas Cleaning	97
	7.1.3 Sulfuric Acid Plants	100
	7.1.4 Sulfur Plants	103
	7.1.5 Molecular Sieves	103
	7.1.6 Dimethylaniline Scrubbing	103
	7.1.7 SO_2 Absorbent Systems	104

CONTENTS (continued)

		Page
	7.2 CAPITAL, OPERATING AND ANNUALIZED CAPITAL COST EQUATIONS	106
8.0	CONVERSION OF OIL- OR GAS-FIRED BOILERS TO COAL-FIRED	128
9.0	REFERENCES	131
APPENDIX I		134
APPENDIX II		141

LIST OF FIGURES

		Page
1.	Empirical correction factors vs. penetration	45
2A.	Cumulative size - asphalt plant dust	54
3A.	Fractional efficiency curves	55
2B.	Cumulative size - open hearth dust	59
3B.	Fractional efficiency curves	60
4.	Plot of percentile vs. Z	63

LIST OF TABLES

		Page
1A.	Industries and processes by the standard industrial classification code	5
1B.	Combustion processes	18
2.	Pollution reduction devices or methods	20
3A.	Device matrix.	22
3B.	Combustion process	38
4.	Empirical correction factors	44
5.	Tandem efficiencies by empirical method.	46
6.	Tandem efficiencies by analytical method	51
7A.	Efficiency calculations - comparison of algorithms- Example A.	56
7B.	Efficiency calculations - comparison of algorithms- Example B.	61
8.	Selected dusts - size parameters	67
9.	Utility unit costs for particulate control systems	92
10.	SO_2 concentration limitations in the application of SO_2 control systems	95
11.	SO_2 desulfurization processes.	105
12.	Chemical and utility unit costs for desulfurization processes.	141

1.0 INTRODUCTION

The control cost segment of the current version of the Implementation Planning Program (IPP) generates capital and operating cost data resulting from the simulated application of specified particulate and SO_2 control devices or systems to each point source identified in the primary data file.

The point sources themselves in this current version of IPP are identified by four-digit Standard Industrial Classification (SIC) codes and associated two-digit process codes. This list was based upon information available to the National Air Pollution Control Agency (NAPCA), which funded development of the IPP, and is primarily coordinated with the National Emission Data Bank maintained at that time by NAPCA. Since IPP has become operational, NAPCA has been subsumed into the Environmental Protection Agency, and the National Emission Data Bank has greatly expanded. The SIC-process code list has not been materially changed since its inception, however.

This SIC-process code list is related to appropriate particulate and SO_2 control devices via a control device applicability matrix. Only one device with its specified removal efficiency value can be applied at a time. There is no capability to use tandem particulate removal devices to achieve desired levels of control.

Device removal efficiency was preset in the program at three levels for each particulate control device, corresponding to high, intermediate, and low removal efficiency. Cost data generated for

particulate control devices was thus related to the specified device at three levels of pollutant removal efficiency. SO_2 control costs, however, were determined at the one specified level of SO_2 removal capability for each applicable control process.

For the control cost segment of the IPP to provide an effective contribution to the objectives of the program, there is a need for periodical review of the methodology itself, and an update of both applicable technology and cost data. The following report covers such a review and update comprising:

1. Restructuring of the SIC's and process groupings;
2. Expansion of the control device applicability matrix to include use of tandem particulate control devices as well as SO_2 control processes; emphasis is on devices actually used;
3. Determination of overall removal efficiency of tandem particulate removal devices;
4. Relating reported removal efficiency of particulate control devices to specific SIC and process codes rather than an established value for each device;
5. Updating or developing new cost equations, and updating unit cost data.

2.0 REDEFINITION OF SIC-PROCESS CODES

The objective of this task as defined by the EPA Project Officer was to expand the SIC-process code list to include the latest possible information in defining SIC's and processes that, in RTI's judgment, were eligible to be defined as point sources for the National Emission Data Bank, and to restructure the list where necessary into economically grouped SIC units. "Point sources" in this context has been taken to mean processes that are capable of emitting 100 or more tons per year of either particulate matter or sulfur oxides. Accordingly, RTI has developed the list of redefined SIC-process codes presented as table 1. Each SIC-process code has the process defined. Many processes have been added to this list, and the combustion list has been lengthened considerably.

It should be noted that there are combustion process codes that are not in the format "XO" of those in the existing IPP list, and for that reason "XO," where it appears in the SIC-oriented list, should be taken to mean "XO and 9X," since combustion processes now are numbered 00, 10, 20, 30, 40, 50, 60, 70, 80, and 90 through 99. It should also be noted that, because the list has been regrouped as discussed below, in many cases there are more than 9 unit process types within an "SIC code." When this occurs, the reserved combustion numbers 10, 20, 30,..., have been skipped so that there will be no possible confusion. For example, SIC-process code 071310 unambiguously denotes coal combustion, $>10^8$ Btu/hr, general pulverized, as used in grist mills, including custom flour mills.

In order to show more explicitly the economic relationship between many unit processes, the EPA Project Officer requested that detailed four-digit SIC codes be achieved in favor of a grouping under a general two-digit followed by "00" SIC "code." This has been done as much as RTI judged desirable. For example, SIC "code" 1100 includes SIC codes 1111, 1112, 1212, and 1213, as originally assigned by the U.S. Department of Commerce. Each of these generalizations has been shown explicitly in the list. One side effect of this approach has been to materially shorten the list of codes in those cases where an essentially identical polluting process is used in several SIC's that are grouped together.

2.1 REFERENCES

In addition to use of the documents listed below, extensive personal contacts with other RTI personnel and with various EPA personnel in the Industrial Studies Branch, the National Air Data Branch, and elsewhere, were made in verifying identification of sources, their potential for emission, emission factors, and Source Classification Codes of the National Emissions Data Bank.

1. Standard Industrial Classification Code Manual, U.S. Department of Commerce.
2. AP-42.
3. APTD-1135.

Table 1.(A). Industries and processes by the standard industrial classification code

0714 Corn Shelling, Hay Baling, and Threshing Service

- XO Combustion
- 01 Corn Shelling
- 02 Hay Baling
- 03 Threshing

0723 Grist Mills, Including Custom Flour Mills

- XO Combustion
- 01 Shipping or receiving
- 02 Transferring, conveying, etc.
- 03 Screening and cleaning
- 04 Drying
- 05 Processing corn meal
- 06 Processing soybeans
- 07 Cleaning barley or wheat
- 08 Cleaning milo
- 09 Milling barley flour
- 11 Barley feed manufacturing

0724 Cotton Ginning and Compressing

- XO Combustion
- 01 Unloading fan
- 02 Cleaner
- 03 Stick and burr machine
- 04 Miscellaneous

1000 Metal Ore Mining (includes 1000 to 1099)

- XO Combustion
- 01 Shaft mining, general
- 02 Strip mining, general
- 03 Open pit mining, general
- 04 Crushing, general
- 05 Drying, general
- 06 Gold processing
- 07 Molybdenum milling
- 08 Titanium pickling

Table 1.(A)(con.)

1100 Coal Mining (includes 1111, 1112, 1211, 1212, and 1312)

XO	Combustion
01	Shaft mining, general
02	Strip mining, general
03	Pit mining, general
04	Fluidized bed dryer
05	Flash dryer
06	Multilouvered dryer
07	Continuous carrier dryer
08	Rotary dryer
09	Cascade dryer
11	Crushing
12	Screening and sizing

1400 Mining and Quarrying of Nonmetallic Minerals, Except Fuels

XO	Combustion
01	Mining, general
02	Rock, primary crushing
03	Rock, secondary crushing and screening
04	Rock, tertiary crushing and screening
05	Rock, recrushing and screening
06	Rock, fines mill
07	Rock, screening, conveying, and handling
09	Phosphate rock, drying
11	Phosphate rock, grinding
12	Phosphate rock, transfer and storage
13	Phosphate rock, storage pile
14	Ceramic clay, drying
15	Ceramic clay, grinding
16	Ceramic clay, storage
17	Fly ash, sintering
18	Clay and coke mixed, sintering
19	Clay and coke mixed, crushing and screening
21	Natural clay, sintering
22	Natural clay, crushing and screening
23	Limestone crushing, primary
24	Limestone crushing, secondary
25	Lime kiln, vertical
26	Lime kiln, rotary
27	Phosphate rock, rotary kiln
28	Phosphate rock, grinding
29	Sintering, not elsewhere classified
31	Grinding,not elsewhere classified
32	Drying, not elsewhere classified
33	Transfer and storage, not elsewhere classified
34	Barium ore grinding
35	Barium reduction kiln

Table 1.(A)(con.)

2010 Manufacturing: Meat Products (includes 2010 to 2019)

XO Combustion
01 Meat smoking

2040 Grain Mill Products (includes 2040 to 2049)

XO Combustion
01 Shipping or receiving
02 Transferring, conveying, etc.
03 Screening and cleaning
04 Drying
05 Cornmeal processing
06 Soybean processing
07 Barley or wheat cleaning
08 Milo cleaning
09 Barley flour milling
11 Alfalfa grinding
12 Alfalfa dehydrating
13 Rice milling
14 Wet corn milling

2060 Manufacturing: Sugar (includes 2060 to 2069)

XO Combustion
01 Open field burning
02 Bagasse burning

2077 Animal and Marine Fats and Oils

01 Fish scrap processing driers

2080 Manufacturing: Beverages (includes 2080 to 2089)

XO Combustion
01 Grain handling
02 Drying spent grains

2090 Manufacturing Miscellaneous Food Preparations and Kindred Products (includes 2090 to 2099)

XO Combustion
01 Coffee roasting, direct fired
02 Coffee roasting, indirect fired
03 Coffee roasting, stoner and cooler
04 Coffee roasting, instant coffee spray dryer

2100 Tobacco Manufactures (includes 2100 to 2199)

XO Combustion
01 Mechanical steamming

Table 1.(A)(con.)

2200 Textile Mill Products (includes 2200 to 2299)

XO	Combustion
01	Fiberglass, regenerative furnace
02	Fiberglass, recuperative furnace
03	Fiberglass, forming
04	Fiberglass, curing oven

2400 Lumber and Wood Products including Furniture (includes 2400 to 2599)

XO	Combustion
01	Conical burner
02	Debarking machine, saw, planers, sanders, etc.
03	Drying kilns
04	Creosote, pressure treating

2600 Manufacturing: Paper and Allied Products

XO	Combustion
01	Kraft process, recovery boilers
02	Kraft process, smelt dissolving tank
03	Kraft process, lime kiln
04	Kraft process, fluid bed calciner
05	Kraft process, oxidation tower
06	Fiberboard manufacture, drying

2812 Manufacturing: Alkalies

XO	Combustion
01	Conveying, transferring loading soda ash

2816 Manufacturing: Inorganic Pigments

XO	Combustion
01	Calcination
02	Digestion
03	Chloride process
04	Chloride coke or ore drying
05	Ore grinding
06	Varnish reaction kettles

2819 Industrial Inorganic Chemicals, Not Elsewhere Classified

XO	Combustion
01	Phosphoric acid, thermal process
02	Sulfuric acid, contact process
03	Sulfuric acid, lead chamber process
04	Sulfur recovery incinerator
05	Sulfur, Claus
06	Calcium carbide, coke dryer
07	Calcium carbide, electric furnace
08	Calcium carbide, stack
09	Calcium carbide, calcination

Table 1.(A)(con.)

2821 Manufacturing: Plastic Materials, Synthetic Resins, and Non-vulcanizable Elastomers

XO Combustion
01 Polyvinyl chloride process
02 Polypropylene process
03 Storage and handling of resins

2822 Manufacturing: Synthetic Rubber (Vulcanizable Elastomers)

XO Combustion
01 Reactor
02 Blow-down tanks
03 Drying

2824 Manufacturing: Synthetic Organic Fibers, Except Cellulosic

XO Combustion
01 Nylon finishing (oil vapor or mist)
02 Polyester finishing (oil vapor or mist)

2840 Manufacturing: Soap, Detergents, and Cleaning Preparations, Perfumes, Cosmetics, and Other Toilet Preparations (includes 2840 to 2849)

XO Combustion
01 Detergent spray dryer

2850 Manufacturing: Paints, Varnishes, Lacquers, Enamels, and Allied Products (includes 2850 to 2859)

XO Combustion
01 Pigment handling
02 Pigment kiln

2861 Manufacturing: Gum and Wood Chemicals

XO Combustion
01 Charcoal manufacturing, without chemical recovery plant

2870 Manufacturing: Agricultural Chemicals

XO Combustion
01 Nitrate fertilizer, dryers and coolers, with prilling tower
02 Nitrate fertilizer, prilling tower
03 Nitrate fertilizer, dryers and coolers, with granulator
04 Nitrate fertilizer, granulator
05 Normal super phosphate, grinding and drying
06 Ammonium or diammonium phosphate, dryer and cooler
07 Ammonium or diammonium phosphate, ammoniator-granulator
08 Ammonium phosphate, cage mill
09 Screening and bagging
11 Mixing fertilizer
12 Mixing pesticides

Table 1.(A)(con.)

2893 Manufacturing: Printing Ink

XO	Combustion
01	Pigment mixing

2895 Manufacturing: Carbon Black

XO	Combustion
01	Channel process
02	Furnace process, oil
03	Furnace process, gas

2899 Manufacturing: Chemicals and Chemical Preparations Not Elsewhere Classified

XO	Combustion
01	Rotary frit furnace

2911 Petroleum Refining

XO	Combustion (boilers and process heaters included)
01	Fluid cracking units
02	Moving-bed catalytic cracking units
03	Fluid coking units
04	Compressor internal combustion engines
05	Hydrocracking, fixed bed catalytic reactor H_2S
06	Hydrogen treating
07	Chemical treating
08	Physical treating
09	Natural gas flares

2950 Manufacturing: Paving and Roofing Materials (includes 2951 and 2952)

XO	Combustion
01	Asphalt batching, rotary dryer
02	Asphalt batching, other sources
03	Asphalt roofing, asphalt blowing
04	Asphalt roofing, felt saturation, dipping
05	Asphalt roofing, felt saturation, spraying
06	Asphalt roofing, felt saturation, dipping and spraying
07	Asphalt batching and quarrying, rock crushing

3210 Manufacturing: Glass Products (includes 3211, 3221, 3229, and 3231)

XO	Combustion
01	Soda lime glass melting

3241 Manufacturing: Hydraulic Cement

XO	Combustion
01	Quarrying general
02	Rock, primary crushing
03	Rock, secondary crushing

04	Rock, tertiary crushing
05	Rock, recrushing and screening
06	Rock, fines mill
07	Raw material storate
08	Dry process, grinding and blending
09	Dry process, kilns
11	Dry process, finishing grinding
12	Wet process, grinding and blending
13	Wet process, kilns
14	Wet process, finish grinding
15	Packaging

3250 Manufacturing: Clay Products and Pottery (includes 3250 and 3269)

XO	Combustion
01	Ceramic clay, drying kilns
02	Ceramic clay, grinding
03	Ceramic clay, storage
04	Flay ash sintering
05	Clay mixed with coke sintering
06	Natural clay sintering
07	Brick, pipe, etc., raw material handling
08	Brick, pipe, etc., raw material storage
09	Brick, pipe, etc., tunnel kilns, gas-fired
11	Brick, pipe, etc., tunnel kilns, oil-fired
12	Brick, pipe, etc., tunnel kilns, coal-fired
13	Brick, pipe, etc., periodic kilns, gas-fired
14	Brick, pipe, etc., periodic kilns, oil-fired
15	Brick, pipe, etc., periodic kilns, coal-fired

3270 Concrete Products (includes 3271, 3272, and 3273)

XO	Combustion
01	Concrete batching
02	Quarrying general
03	Rock, primary crushing
04	Rock, secondary crushing
05	Rock, tertiary crushing
06	Rock, recrushing and screening
07	Rock, fines mill
08	Raw material storage
09	Dry process, grinding and blending
11	Dry process, kilns
12	Dry process, finishing grinding
13	Wet process, grinding and blending
14	Wet process, kilns
15	Wet process, finishing grinding
16	Packaging

3274 Manufacturing : Lime

XO	Combustion
01	Crushing, primary
02	Crushing, secondary
03	Calcining, vertical kiln
04	Calcining, rotary kiln

Table 1.(A)(con.)

3275 Gypsum Products

XO Combustion
01 Handling
02 Sheetrock cutting and trimming

3281 Cut Stone and Stone Products

XO Combustion
01 General

3291 Manufacturing: Abrasive Products

XO Combustion
01 General crushing

3295 Minerals and Earths, Ground or Treated

XO Combustion
01 Crushing, general
02 Conveying, screening and shaking
03 Storage piles
04 Drying, general

3296 Manufacturing: Mineral Wool

XO Combustion
01 Mineral wool, cupola
02 Mineral wool, reverberatory furnace
03 Mineral wool, blow chamber
04 Mineral wool, curing oven
05 Mineral wool, cooler

3312 Blast Furnaces (including Coke Ovens, Steel Works, and Rolling and Finishing Mills)

XO Combustion
01 By product coking, unloading
02 By product coking, charging
03 By product coking, coking cycle
04 By product coking, discharging
05 By product coking, quenching
06 By product coking, underfiring
07 Beehive ovens
08 Pig iron, blast furnace, ore charge
09 Pig iron, blast furnace, agglomerates charge
11 Pig iron, sintering, wind box
12 Pig iron, sintering, discharge
13 Steel, open hearth, no oxygen lance
14 Steel, open hearth, oxygen lance
15 Steel, basic oxygen
16 Steel, electric arc, no oxygen lance
17 Steel, electric arc, oxygen lance
18 Scarfing
19 Bessemer

Table 1.(A)(con.)

3313 Ferroalloy Manufacturing

XO	Combustion
01	Open furnace 50% FeSi
02	Open Furnace 75% FeSi
03	Open furnace 90% FeSi
04	Open furnace silicon metal
05	Open furnace silico-manganese

3320 Iron Foundries (includes 3321 and 3322)

XO	Combustion
01	Scrap preparation (principally for electric furnaces)
02	Cupola
03	Reverberatory furnace
04	Electric induction furnace
05	Electric arc furnace
06	Sand handling and preparation
07	Annealing (malleable iron)
08	Inoculation (ductile iron)
09	Casting
11	Casting shakeout
12	Cleaning
13	Finishing

3323 Steel Foundries

XO	Combustion
01	Crucible furnace
02	Pneumatic converter furnace
03	Electric arc furnace
04	Electric induction furnace
05	Open hearth furnace
06	Open hearth, oxygen lanced
07	Casting
08	Casting shakeout
09	Cleaning
11	Finishing

3331 Copper Smelting lbs/ton of ore concentrate

XO	Combustion
01	Roaster
02	Reverberatory furnace (w/o roaster)
03	Reverberatory furnace (w/roaster)
04	Converter (w/o roaster)
05	Converter (w/roaster)
06	Refining
07	Materials handling

3332 Lead Smelting

XO	Combustion
01	Downdraft sinterer & crushing
02	Updraft sinterer & crushing

Table 1.(A)(con.)

03 Blast furnace
04 Reverberatory furnace
05 Materials handling

3333 Zinc Smelting

XO Combustion
01 Downdraft roaster-sinterer
02 Updraft roaster-sinterer
03 Updraft recirculating roaster-sinterer
04 Roaster (separate sintering)
05 Sintering
06 Horizontal retorts
07 Vertical retorts
08 Electrolytic reducer
09 Materials handling

3334 Primary Production of Aluminum

XO Combustion
01 Bauxite grinder
02 Calciner
03 Anode baking furnace
04 Prebaked reduction cell
05 Horizontal stud Soderburg cell
06 Vertical stud Soderburg cell
07 Materials handling

3339 Primary Smelting and Refining of Nonferrous Metals, Not Elsewhere Classified

XO Combustion
01 Ore handling and grinding
02 Roasting
03 Sintering
04 Converting
05 Reducing
06 Refining

3340 Secondary Smelting, Refining, Casting, Rolling, Drawing, and Extruding of Nonferrous Metals (includes 3340 to 3369)

XO Combustion
01 Scrap preparation
02 Aluminum, sweating furnace
03 Aluminum, smelting crucible furnace
04 Aluminum, smelting reverberatory furnace
05 Aluminum, chlorination station
06 Brass or bronze, blast furnace
07 Brass or bronze, crucible furnace
08 Brass or bronze, electric induction furnace
09 Brass or bronze, cupola
11 Brass or bronze, reverberatory furnace

Table 1.(A)(con.)

12	Brass or bronze, rotary furnace
13	Lead, pot furnace
14	Lead, reverberatory furnace
15	Lead, blast furnace/cupola
16	Lead, rotary reverberatory
17	Magnesium, pot furnace
18	Zinc, retort reduction furnace
19	Zinc, horizontal muffle furnace
21	Zinc, pot furnace
22	Zinc, kettle sweat furnace, general scrap charge
23	Zinc, kettle sweat furnace, residual scrap charge
24	Zinc, reverberatory sweat furnace, general scrap charge
25	Zinc, reverberatory sweat furnace, residual scrap charge
26	Zinc, galvanizing kettles
27	Zinc, calcining kiln
28	Nickel flux furnace
29	Zirconium oxide kiln
31	Other metal furnaces not classified
32	Sand handling and preparation
33	Casting
34	Casting shakeout
35	Cleaning
36	Finishing

3390 Iron and Steel Forgings, Nonferrous Forgings, and Miscellaneous Primary Metal Products (includes 3390 to 3399)

XO	Combustion
01	Forge furnaces

3400 Fabricated Metal Products Except Ordnance Machinery and Transportation Equipment (includes 3400 to 3499)

XO	Combustion
01	Cleaning
02	Surface coating
03	Milling

3500 Manufacturing: Machinery Except Electrical (includes 3500 to 3599)

XO	Combustion
01	Surface coating

3600 Manufacturing: Electrical Machinery, Equipment, and Supplies (includes 3600 to 3699)

XO	Combustion
01	Surface coating

Table 1.(A)(con.)

3624	Carbon and Graphite Products	
	XO	Combustion
	01	Furnace electrode calcination
	02	Furnace electrode mixing
	03	Furnace electrode pitch treating
	04	Furnace electrode baking furnace
3700	Manufacturing: Transportation Equipment (includes 3700 to 3799)	
	XO	Combustion
	01	Surface coating
3800	Manufacturing Professional, Scientific and Controlling Instruments; Photographic and Optical Goods; Watches and Clocks (includes 3800 to 3899)	
	XO	Combustion
	01	Surface coating
3900	Miscellaneous Manufacturing Industries (includes 3900 to 3999)	
	XO	Combustion
	01	Surface coating
4953	Refuse Systems	
	XO	Combustion
	01	Municipal, incinerator, multiple chamber
	02	Open burning
	03	Industrial/commercial, multiple chamber
	04	Industrial/commercial, single chamber
	07	Industrial/commercial, controlled air
	08	Flue-fed, single chamber
	09	Flue-fed, afterburners and draft controls
	11	Domestic, single chamber, without primary burner
	12	Domestic, single chamber, with primary burner
	13	Pathological
	14	Conical burner, municipal refuse
	15	Conical burner, wood waste
	16	Automobile body incinerator
5098	Lumber and Construction Materials, Wholesale Trade	
	XO	Combustion
	01	Sand handling
	02	Crushed stone handling

Table 1.(A)(con.)

5153 Grain, Wholesale Trade

XO	Combustion
01	Terminal elevators, shipping or receiving
02	Terminal elevators; transferring, conveying, etc.
03	Terminal elevators, screening and cleaning
04	Terminal elevators, drying
05	Country elevators, shipping or receiving
06	Country elevators; transferring, conveying
07	Country elevators, screening and cleaning
08	Country elevators, drying

Table 1.(B). Combustion processes

00	All not listed
10	Coal, greater than 10^8 Btu/hr, general pulverized
20	Coal, greater than 10^8 Btu/hr, wet bottom pulverized
30	Coal, greater than 10^8 Btu/hr, dry bottom pulverized
40	Coal, greater than 10^8 Btu/hr, cyclone pulverized
50	Coal, less than 10^8 Btu/hr, spreader stoker w/o fly ash reinjection
60	Coal, less than 10^8 Btu/hr, spreader stoker w/fly ash reinjection
70	Coal, less than 10^8 Btu/hr, overfeed stoker w/o fly ash reinjection
80	Residual oil, power plant
90	Distillate oil, power plant
91	Residual oil, other than power plant
92	Distillate oil, other than power plant
93	Gas, power plant
94	Gas, other than power plant
95	Wood
96	Mixed fuel combusted at same time
97	Mixed fuel combusted at different times

3.0 DEVICE MATRIX

In table 2 are listed the pollution reduction devices and methods displayed in the Device Matrix in table 3 under columns X, Y, and Z.

Alphanumeric reference notes shown associated with device selection X, Y, or Z refer to the data sources listed at the end of table 3.

The industrial processes referred to in the Device Matrix, table 3, are those listed by SIC code in table 1.

The development of the combined efficiency of in-tandem particulate devices is discussed in sections 4 and 5.

The development of the capital and expense costs for the control methods and devices specified in the Device Matrix is discussed in sections 6, 7, and 8.

The Device Matrix, table 3, reports the type of control equipment used for primary particulate control, under column X, for secondary control in tandem, under column Y; and for SO_2 control, under column Z. Under the two columns labelled "Efficiency," the first shows the efficiency of particulate control of the devices under x and y combined. The second column gives the efficiency of control of SO_2 emissions under z.

In the columns labelled "Capital Costs," the numbers identify the appropriate capital cost equations under "x" for primary particulate reduction, under "y" for secondary devices, and under "z" for SO_2 removal. Cost equations are assigned according to the severity of usage in the specific SIC process and are not necessarily related to reduction efficiency. Thus, corrosive conditions, difficulty of separation, retrofit costs, etc., are judgment factors that control the cost of a particular device category. These refer to installed capital costs only.

Table 2. Pollution reduction devices or methods

Identification Number	Control Device/Method
000	No Equipment
001	Wet Scrubber - High Efficiency
002	Wet Scrubber - Medium Efficiency
003	Wet Scrubber - Low Efficiency
004	Gravity Collector - High Efficiency
005	Gravity Collector - Medium Efficiency
006	Gravity Collector - Low Efficiency
007	Centrifugal Collector - High Efficiency
008	Centrifugal Collector - Medium Efficiency
009	Centrifugal Collector - Low Efficiency
010	Electrostatic Precipitator-High Efficiency
011	Electrostatic Precipitator - Medium Efficiency
012	Electrostatic Precipitator - Low Efficiency
013	Gas Scrubber (general, not classified)
014	Mist Eliminator - High Velocity
015	Mist Eliminator - Low Velocity
016	Fabric Filter - High Temperature
017	Fabric Filter - Medium Temperature
018	Fabric Filter - Low Temperature
019	Catalytic Afterburner
020	Catalytic Afterburner with Heat Exchanger
021	Direct Flame Afterburner
022	Direct Flame Afterburner with Heat Exchanger
023	Flaring
024	Switch from Residual Oil to Coal with Specified %S
025	Switch from Distillate Oil to Coal with Specified %S
026	Switch from Gas to Coal with Specified %S
027	Eliminate Coal Combustion
028	Eliminate Coal and Residual Oil Combustion
029	Change All Fuel to Natural Gas
030	No Fuel Use Over a Maximum Sulfur Content (Specified by Uses in Regional Data Base)
031	Same as Device 030 but with Second Allowable Sulfur Content
032	Same as Device 030 but with Third Allowable Sulfur Content
033	Add-On Double Absorption (Sulfuric Acid)
034	Wellman-Lord System (with or without SO_2 reduction)
035	Magnesia (MgO) Slurry System
036	Double Alkali System
037	Citrate System
038	Ammonia System

Table 2 (con.)

Identification Number	Control Device/Method
039	Catalytic Oxidation ("Cat-Ox")
040	Alkalized Alumina
041	Dry Limestone Injection
042	Wet Limestone Scrubbing
043	Sulfuric Acid Plant - Single Absorption Contact Process
044	Sulfuric Acid Plant - Double Absorption Contact Process
045	Sulfur Plant
046	Process Change
047	Vapor Recovery System (including condensers, hooding, and other enclosures
048	Activated Carbon Adsorption
049	Liquid Filtration System
050	Packed-Gas Absorption Column
051	Tray-Type Gas Absorption Column
052	Spray Tower (Gaseous Control Only)
053	Venturi Scrubber (Gaseous Control Only)
055	Afterburner-Direct Flame, Regenerative
056	DMA Absorption
057	Molecular Sieves
058	Sodium Phosphate("Powerclaus") System
059	Screen Filter

NOTE: Whenever a range of efficiency is reported in the literature, an attempt is made to show this by assigning a different index within the device code as illustrated below:

	Wet Scrubbers	Cyclones	Electrostatic Precipitators %
Highest Efficiency	001	007	010
Intermediate Efficiency	002	008	011
Lowest Efficiency	003	009	012

The actual reported efficiency is shown under the "Efficiency Entry" columns x, y, and z in table 3.

Table 3. (A) Device Matrix

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(1),(6)	0714-01	008			700		2		
	-02	009*			600*		2		
	-03								
(1),(6),	0723-01	007*			850*		2		
(5),(7)	-02	008			700		2		
	-03	008	018		990		2	2	
	-04	018*			990*		2		
	-05								
	-06								
	-07								
	-08								
	-09								
	-11								
	0724-01	004*			600*		1		
	-02	007*			850*		2		
(2c),(12)		018			990		2		
(6)		005	009		700		1	2	
(6)	-03	007			950		2		
	-04	004*			600*		1		
		018			990*		2		
(6),(2c), (12)		005	018		990		1	2	
(7)	1000-04	001			950		3		
	-05	007			800		2		
		018			995		2		
		007	001		958		2	3	

*Asterisk indicates possible control devices and estimated efficiencies. Data not asterisked are definite literature references.

Capital Cost Indices:
1 = most expensive, or, only one cost equation
2 = intermediate cost, for the indicated class of equipment
3 = least cost

**See source references at the end of section (B) of this table.

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(3a),(6), (7)	1100-04	001			997		3		
	-06	002			940		3		
		003*			800*		3		
(3a)		007			820		2		
(6)		008*			750*		2		
		007	001		999		2	3	
(3a)	-05	007			820		2		
(6)		009*			600*		2		
(1),(2c), (6), (7)	1400-03	007			800		2		
	-04	001			990		3		
	-05	002			950		3		
	-06	007	001		999		2	3	
	-07								
	-09								
	-14								
	-17								
	-18								
	-19								
	-21								
	-22								
	-23								
	-24								
	-27								
	-29								
	-32								
	-34								
	-35								
(1),(2c)	-11	007			800		2		
(6),(7)	-12	017			995		2		
	-16	007	017		999		2	2	
	-28								
	-33								
(1),(2c), (6),(7)	-15	007			800		2		
	-25	010			990		2		
	-26	011			950		2		
	-31	012			900		2		
		017			990		2		
		007	010		990		2	2	
		007	011		961		2	2	
		007	012		936		2	2	
		007	017		990		2	2	

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(1),(6), (12)	2010-01	003			400		3		
		012			650		2		
		021			650		1		
		003	012		670		3	2	
(1),(6), (7)	2040-01	007	018		990		2	2	
	-02								
	-03								
	-05								
	-06								
	-07								
	-08								
	-09								
	-11								
(1), (6)	-04	007			950		2		
(7),(5)	-12	008			900		2		
	-13	007*	018*		999*		2	2	
	-14								
(2c),(6)	2060-02	007*			850*		2		
		008			700		2		
		001			950		3		
		003*			800*		3		
		008	001		955		2	3	
(1),(6)	2077-01	007	021		990		2	2	
	2080-01	007*			850*		2		
(12)	-02	008			800		2		
		009*			600*		2		
(13)		018			990		2		

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(1),(6)	2090-01	008			800		2		
(12)	-02	009*			600*		2		
		021			950		1		
		008	021		950		2	1	
	-03	008			800		2		
		009			700		2		
	-04	008	002		950		2	3	
		017*			999*		2		
	2100-01	008			800		2		
(1),(6)	2200-01	003		042	600	850	2		1
	-02	017		036	990	900	2		1
		003	017		990		2	3	
(1),(6)	-03	022			950		1		
	-04								
(1),(6)	2400-01	003			850		3		
	-02	007			800		2		
	-03	007			800		2		
		021			950		1		
		007	021		950		2	1	
(1)	-04	022			990		1		
(2c),(6), (4b)	2600-01	001		042	966	850	2		1
		002		036	874	900	2		1
		003			700		2		
		007			800		2		
		010			970		2		
		011			900		2		
	-02	003			750		3		
		003	015		950		3	2	
	-03	001			994		3		
	-04	007	001		994		2	3	
		009	001		970		2	3	
		003			910		3		
	-06	021			950		1		
(1),(6)	2812-01	001*			950*		3		
		007*			850*		2		
	2816-01			036		900			1

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(4b)	2819-01	001	014		999		1	1	
		010			999		1		
		011			963		1		
(4b),(14)	-02	001		038	400	900	1		1
		010		057	990	980	1		1
		012		033	900	995	1		1
		014		036	940	900	1		1
		010	014	034	999	900	1	1	
(4b),(14)	-03	010	014	042	999	850	1	1	1
		015		036	400	900	1		1
				057		980			1
				034		900			1
(6)	-05			034		900			1
	-06	001*			950		3		
		007			850		2		
		007	001*		975		2	3	
	-07	001*			950		2		
	-08								
	-09								
(1),(6)	2821-01	002			940		3		
	-02	002	021		950		3	1	
		018			990		2		
	-03	018			990		2		
		007			850*		2		
(1),(6)	2822-01	017	021		980		2	1	
	-02	001			900*		3		
	2824-01	021*			990		1		
	-02	015*			990			2	

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(1), (6)	2840-01	007			850		2		
		007	001		970		2	3	
		007	002		950		2	3	
		007	003		920		2	3	
(1), (6)	2850-01	002			900		3		
	02	002			900		3		
		004	021		900		1	1	
		018			990		2		
(6)	2861-01	021			990*		1		
(6),	2870-01	007	003		900		2	3	
	-02	007			700		2		
	-03	001			950		3		
	-04								
(6)(7)	-05	007	003		960		2	3	
		017			990		2		
(6)(7)	-06	001			996		3		
		002			810		3		
		017			990		2		
(6)(7)	-07	007			950		2		
		007	001		999		2	3	
		017			990		2		
(7)	-08	003			810		3		
	-09	007	002		960		2	3	
	-11								
	-12								
(1), (6)	2893-01	002	021		900		3	1	
		001	021		970		3	1	
(4b), (6)	2895-02	007			900		2		
	-03	007	001		970	200	2	3	
		016			990		2		
		010			970		2		
		011			930		2		

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(6), (1)	2899-01	003			700		2		
		016			990*		1		
(3a),(6)	2911-01	010			997		2		
	-02	011			950		2		
	-03	012			810		2		
(4b),(10)		007	010		998		2	2	
		008			800		2		
		007			900		2		
(14)	-01			044		995			1
	-02			045		900			1
	-03			034		900			1
	-04								
	-05								
	-06								
	-07								
	-08								
(1),(3a), (6),(7)	2950-01	007			900		2		
(1)	-02	008			700		2		
		009			670		2		
(3a)(6)		001			999		3		
(1)(7)		002			850		3		
		007	002		950		2	3	
(1)		007	001		999		2	3	
		017			998		2		
(6)	-03	003	012		850		3	2	
(1)		001	022		980		3	1	
(6)		012			600		3		
(1)	-04	001			860		3		
	-05	003			710		3		
(1)	-06	003	012		940		3	2	
		001			860		3		
		007	017		990		2	2	
(1)	-07	008	002		950		2	3	
		018			999		2		

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(1), (6)	3210-01	001			560		3		
		016			990		2		
(2),(c),	3241-02	007			700		2		
(1)	-03	007	018		990		2	2	
	-04								
	-05								
	-06								
	-08								
	-11								
	-12								
	-14								
	-15								
(6),(2c),	-09	007			800		2		
(4b)		008			700		2		
		010			988		2		
		007	010		995		2	2	
		008	010		900		2	2	
		009	010		830		2	2	
		007	016		995		2	2	
(2c)	-13	010			995		2	2	
		012			900		2		
		007	010		995		2	2	
		016			998		2		
(6), (3a)	3250-01	008			750		2		
(7)	-04	008	002		900		2	3	
	-05	008	016		995		2	2	
	-06	008	010		990		2	3	
	-09	007	001		990		2	3	
	-11								
	-12								
	-13								
	-14								
	-15								
(6)	-02	008			750		2		
	-03	018*			990*		2		
	-07								
	-08								

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(2c)	3270-01	018			990		2		
	-08	002			900		3		
(2c), (6)	-03	009	003		800		2	3	
	-04	018*			990		2		
	-05								
	-06								
	-07								
	-09								
	-15								
	-16								
(2c)	-11	009	003		800	200	2	3	
	-14	016*			990*		2		
(2c),(6)	3274-01	007			850		2		
	-02	008			700		2		
		009			650		2		
		007	017		990		2	2	
		009	017		950		2	2	
(2c)(6)	-03	007			850		2		
	-04	008			700		2		
		009			650		2		
		007	016		999		2	2	
		007	011		950		2	3	
		007	001		970		2	3	
		007	002		960		2	3	
(6)	3275-01	018			998		2		
	-02	007	010		990		2	3	
(6),(7)	3281-01	007			850*		2		
		018			990		2		
		008			700*		2		
	3291-01	008			750*		2		
		007			800*		2		
		018			995*		2		
(1)	3295-01	018			995*		2		
	-02								
	-04								

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(6),(1)	3296-01	007	018		970		2	2	
(4b)	-02	001			600		3		
(6)	-03	001			600		3		
(1)		001	012		680		3	3	
(1)	-04	019			680		1		
(6)		021			500		1		
(4b) (14)	3312-01	016			990		2		
	-02	007	002		925		2	3	
	-05	007	010		990		2	3	
	-06								
(4b)	-03	001			700		3		
		002			600		3		
		010			990		3		
		011			950		3		
	-07	019			980		1		
		021			980		1		
(6),(4b)	-08	007			700		2		
	-09	008			600		2		
		001			980		3		
(6)		002			900		3		
(4b)		011			980		3		
		012			900		3		
		007	001		984		2	3	
		007	002		919		2	3	
		008	001		980		2	3	
		008	002		913		2	3	
		007	011		984		2	3	
(4b)(6)		007	012		919		2	3	
(4b),(6)	-11	007			800		2		
	-12	010			980		1		
		011			940		1		
(4b)(6)		007	010		980		2	1	
		007	011		952		2	1	
		007	001		998		2	2	
(2c)(6)		016			990		1		
(2c),(6)	-13	001			992		1		
(4b)	-14	002			950		1		
		010			999		1		
		011			970		1		
		016			990		1		

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries X+Y	Efficiency Entries Z	Capital Cost Entries X	Capital Cost Entries Y	Capital Cost Entries Z
(3)a)(6)	-15	001			999		2		
(4)b)		010			998		1		
(6)	-16	001			999		1		
(4b),(6)	-17	010			998		1		
	-18	004			600		1		
		002			900		2		
(4b),(6)		010			970		1		
		011			940		1		
		004	002		913		1	2	
(4)(b)	-19	001			999		2		
		010			999		2		
(2c)(3a)	3313-01	001			990		2		
	-02	002			940		2		
(3a)	-03	010			980		3		
	-04	011			940		3		
(3a)	-05	016			989		1		
(2c)(6)	3320-02	001			990		2		
		002			913		2		
		003			885		2		
		011			960		3		
		012			900		3		
		016			998		1		
	-03	016			990		1		
	-04	003			700		2		
		011			970		3		
		012			920		3		
		016			990		1		
(2c)(6)	-05	003			700		2		
	-08	011			970		3		
		012			920		3		
		016			994		1		
	-06	007	001		999		2		
	-12								
	-11								
	-13								
	-09	001			990		3		

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z	
(2c),(6)	3323-01	001			990		2			
		002			880		2			
		011			960		3			
		012			900		3			
	-02	001			950		2			
	-03	003			700		2			
	-04	010			970		2			
		011			920		2			
		016			990		1			
	-05	001			950		2			
	-06	010			999		2			
		011			970		2			
		016			990		1			
	-07	001			990		3			
(2c)(6)	-08	007	001		999		2	3		
	-09									
	-11									
(3a),(6) (14)	3331-01	001		043	950	975	1		1	
		016		044	998	995	1		1	
		001	010	045	998	900	1	1	1	
(3a)(14)	-02	001		034	997	900			1	
	-03	010		037	990	950	1		1	
				043		975			1	
				042		850			1	
				056		980			1	
(3a),(6)(14)	-04	016		043	999	975	1		1	
	-05	010		044	999	995	1		1	
				056		980			1	
(3a)(6)	-06	016			999		2			
	-07									
(4b),(6)	3332-01	016	056	999	980		1		1	
(14)	-02	010	043	960	975		1		1	
	-03		044		995				1	
			036		900				1	
	-04									
	-05									
	-06									
	-07									

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital cost Entries x	Capital cost Entries y	Capital cost Entries z
(4b)(2c)	3333-01	001	010	043	998	975	1	1	1
	-02	010		044	995	995	1		1
	-03	001		037	990	950	1		1
	-04	016		045	999	900	1		1
	-05	007	016	056	999	980	1	1	1
	-06								
	-07								
	-08								
	-09								
(6)(2c)	3334-01	002			830		2		
	-02	003			700		2		
		010			980		2		
	-03	001			980		2		
		012			620		2		
6)(2c)	-04	008			780		2		
(4b)		002			850	200	3		
		003			800	200	3		
		012			870		2		
		007	010		980		2	2	
(6)(2c)	-05	002			780	200	3		
(4b)		003			710	200	3		
		011			930		3		
		007	010		980		2	3	
(6)(2c)	-06	001			960	200	3		
(4b)		003			750	200	3		
		007			950		2		
		010			990		3		
		012			900		3		
		007	010		980		2	3	
(6)	-07	002			830		3		
		003			720		3		
		010			980		3		
(4b)	3339-01	016			999		2		
(4b)	-02	010	001	042	990	850	1	2	1
		012	002	043	950	975	1	1	1
				044		995			1
				045		900			1

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(4b)	-03	007		043	900	975	1		1
		008			800		1		
		010			990		1		
		011			950		1		
		016			990		1		
(4b)	-04	010	016		990		2	1	
	-05	012	016		950		2	1	
	-06								
(3b)(6)	3340-02	001			997		2		
		016			995		1		
(4b)(6)	-03	001	010		990		2	2	
	-04	002	011		950		2	2	
(6)		012			900		2		
3(b)(6)	-05	001			998		1		
		016			950		1		
4(b)	-06	007			900		2		
	-07	008			800		2		
(1)(6)	-08	010			990		1		
		011			950		1		
		016			990		1		
4(b)	-09	001	010		990		2	2	
	-11	002	011		950		2	2	
(3b)(1), (6)	-12	016			997		1		
(3b)(1)(6)	-13	001			992		2	1	
		016			989		1		
(3b)(2c) (4b)	-14	001		042	994	850	2		1
		016		036	993	900	1		1
		001	010		990		2	1	
		002	011		950		2	1	
(2c)(4b)	-15	007		042	900	850	2		1
(3b)(6)	-16	008		036	800	900	2		1
		001			992		2		
		016			989		1		
		010			990		2		
		011			950		2		
(4b)		001	010		990		2	2	
		002	011		950		2	2	

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
2(c)(6)	-17	012			800		2		
		007	016		990		2	1	
2(c)	-18	007	016		990		2	1	
	-19	010			850		1	1	
	-21	011			750		1		
(2c)(b)	-22	022	016		990		1	1	
	-23	016			930		1		
(4b)	-24	001	010		990		2	1	
	-25	002	011		950		2	1	
		010			850		1		
2(c)	-26	016			990		1		
		012			800		2		
2(c)	-27	012			800		2		
2(c)	-01	008			700		2		
	-32	018			990		2		
	-33								
	-34								
	-35								
	-36								
(6)(4b)	3390-01	010			960		3		
		016			990		1		
	3400-01	008*			750*		2		
(1)	-02	021			950		1		
	-03	008*			750*		2		
(6)(1)	3500-01	002			900		3		
	3600-01	021			990		1		
(6)	3624-04	012	620				2		
		001	980				2		
	3700-01								
	3800-01								
(4b)(6)(1)	4953-01	007		042	800	850	2		1
(4b)	-02	008		036	750	900	2		1
(6)	-03	002			800		3		
(1)	-07	001			950		3		
(4b)	-08	010			990		3		

Table 3. (A) (con.)

Reference**	SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
4(b)(6) (1)	-09	021			990		1		
(6) (1)	-11 -12	021			990		1		
(6)(1)	-13	021			990		1		
(6)(1)	-17	021			990		1		
		010			950		3		
		002	017		950		3	2	
(6)(1)	-14 -15	003			700		3		
(6)(1)(2c)	5053-01	007			950		2		
	-02 -03 -04	007	018		995		2	2	
(1)	-05 -06 -07 -08	007			950		2		
(6)	5098-01	007			700		2		
	-02	008			850		2		
		018			990		2		

Table 3. (B) Combustion processes

Reference	** SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(6)	10	007		042	750	850	2		1
	20	008		036	600	900	2		1
	30	009		037	400	950	2		1
		010		034	995	900	2		1
		012		056	800	980	2		1
(9a)†		007	012		880		2		1
		010							
		007							
	40	007		042	400	850	2		1
		008		036	300	900	2		1
		009		037	200	950	2		1
(6a)		010		034	995	900	2		1
		011		056	820	980	2		1
		012			650		2		1
(9a)		001			990		2		1
	50	007		042	950	850	2		1
		008		036	900	900	2		1
(6a)		009		037	750	950	2		1
		010		034	995	900	2		1
(9a)		001		056	990	980	2		1
	60	005		042	300	850	1		1
		006		036	200	900	1		1
		007		034	900	900	2		1
		008		045	800	900	2		1
		009		037	700	950	2		1
		010			995		2		1
		001			990		2		1

†-Calculated from Table 3.

**See source references at the end of this table.

Table 3. (B) (con.)

Reference	** SIC	X	Y	Z	Efficiency Entries x+y	Efficiency Entries z	Capital Cost Entries x	Capital Cost Entries y	Capital Cost Entries z
(6)	70	007		042	950	850	2		1
		008		036	900	900	2		1
		009		034	750	900	2		1
		010		056	995	980	2		1
(9a)		001		037	990	950	2		1
(1)	80	ξ		042	200	850			1
	90	ξ		036	200	950			1
				034	200	900			1
(1)	91	ξ		029					1
				030					1
(1)	92	ξ		029					1
				030					1
	93	ξ							
	94	ξ							
(1)	95	001			950		2		
	96	003			800		2		
	97								

ξ Particulate removal for oil and gas fired utility and commercial boilers has not been successful and is not practiced. SO_2 scrubbing operations do remove some particulates.(1)

Table 3. (A) & (B) Reference sources

A search of available literature was made on actual practice of device selection and reported collection efficiencies. The following documents have been examined to determine the nature of pollutants for each SIC, type of control applied, efficiency of collection, and whether stand-alone or tandem arrangements are practiced. The numbers and letters within parentheses correspond to those listed in the first column of the table.

(1) Air Pollution Engineering Manual-EPA AP-40 2nd Edition, 1973

(2) Particulate Pollutant System Study - Midwest Research Institute

(2)(a) Volume I Mass Emissions, 1971
(2)(b) Volume II Fine Particles, 1971
(2)(c) Volume III Emission Properties, 1971

(3) Air Pollution Control Technology - Industrial Gas Cleaning Institute

(3)(a) September 1972 Issue
(3)(b) December 1970 Issue

(4) Electrostatic Precipitator Technology - Southern Research Institute

(4)(a) Part I - Fundamentals, 1970
(4)(b) Part II - Application Areas, 1970

(5) The Economics of Clean Air - Report to the Congress - December 1970

(6) Air Pollution Emission Factors - EPA - AP42, 1973

(7) Scrubber Handbook - A.P.T. Inc., August 1972 - Vol. I.

(8) Proceedings, Specialty Conference APCA St. Louis Section - March 1973

(9) Evaluation of SO_2 Control Processes EPA Contract CPA 70-68

(9)(a) Task 5 - M. W. Kellogg Company - October 1971
(9)(b) Task 7 - M. W. Kellogg Company - March 1972

(10) Conceptual Design and Cost Study-TVA-EPA PB-222-509-May 1973

(11) Applicability of Reduction to Sulfur Techniques PB-198-407

Allied Chemical Vol. I, Phase I, July 1969

(12) Control Techniques - Particulates AP 51 1969

(13) Control Techniques - Particulates-NATO/CCMS 1973

(14) Control Techniques - Sulfur Oxides - NATO/CCMS 1973

4.0 COMBINED EFFICIENCY OF TWO PARTICULATE MATTER CONTROL UNITS IN TANDEM

The problem of estimating the combined efficiency of two control units in tandem is discussed in this section. The stand-alone rated efficiency of a device treating a particular dust stream is based on the weight percent of the dust removed. The fractional efficiency of removal is high for the large particles and considerably lower for the smaller sizes. In the sub-micron sizes, removal is extremely difficult. When a second control device follows a primary cleaning device, the applied efficiency of the secondary device is lower than its stand-alone rated efficiency on the dust stream entering the primary device. In the following sections, several methods are discussed for evaluating combined efficiency; calculated efficiencies are compared with actual tandem efficiencies reported in the technical literature.

4.1 EMPIRICAL CORRECTION FACTOR METHOD

For the purpose of developing an empirical relationship for the efficiency of two tandem devices, it is assumed that feed to the device is based on processing a standard silica dust with standard particle size distribution.[1] Fractional efficiency in each particle size range for the control devices in question is also known, as found in reference 6.

In the following discussion,

let:

E_1 = rated efficiency of primary device,

E_2 = rated efficiency of secondary device,

AE_2 = applied efficiency of secondary device as affected by its being preceeded by the primary device,

CF = correction factor applied to the rated efficiency of the secondary device to determine its applied efficiency, (AE_2):

$$CF = (1 - AE_2)/(1 - E_2), \qquad (4.1\text{-}1)$$

EOA = overall efficiency of both the primary and secondary devices working in tardem,

$$= 1 - (1 - E_1)(1 - AE_2). \qquad (4.1\text{-}2)$$

Assume, for example, the following devices, from page A-3 of reference 1:

Primary device - Irrigated long-cone cyclone, $E_1 = 0.91$ (rated),

Secondary device - Dry multiple cone cyclone, $E_2 = 0.938$ (rated).

The applied efficiency, correction factor, and overall efficiency are calculated as indicated in the following work sheet:

Size	Weight %		Fractional efficiency of Primary		Weight % Retained by Primary	Weight % Passed by Primary		Fractional efficiency of Secondary		Weight % Retained by Secondary
0-5 μm	20	×	0.63	=	12.6	7.4	×	0.63	=	4.662
5-10	10	×	0.93	=	9.3	0.7	×	0.95	=	0.665
10-20	15	×	0.96	=	14.4	0.6	×	0.98	=	0.588
20-40	20	×	0.985	=	19.7	0.3	×	0.995	=	0.298
>44	35	×	1.0	=	35.0	0	×	1.0	=	0
					91	9.0				6.214

Applied efficiency of secondary, $AE_2 = 6.214/9.0 = 0.69$, and

$$CF = \frac{1 - 0.69}{1 - 0.938} = 5$$

In calculating many of these correction factors (see table 4), a correlation was found between the primary rated efficiency E_1, and CF. Plotting $(1 - E_1)$ vs CF on semi-log coordinates (figure 1) yielded a straight line represented by the following equation:

$$CF = \frac{0.3010 - \log_{10}(1 - E_1)}{0.3642} . \qquad (4.1\text{-}3)$$

Overall efficiency is found from the applied efficiency of the secondary device given by the following equation:

$$AE_2 = 1 - (1 - E_2)\left[\frac{0.3010 - \log_{10}(1 - E_1)}{0.3642}\right] . \qquad (4.1\text{-}4)$$

$$\text{Overall efficiency, } EOA = 1 - \left|(1 - E_1)\left[\frac{0.3010 - \log_{10}(1 - E_1)}{0.3642}\right](1 - E_2)\right| . \qquad (4.1\text{-}5)$$

A computer program generated the matrix of overall efficiencies for the indicated primary and secondary rated efficiencies shown in table 5. Ratings of the rated device efficiencies used in the table are arbitrary. If the actual particle size distribution is known and the fractional efficiencies for the devices have been determined, the algorithm is applicable.

Table 4. Empirical correction factors

Range, Existing Efficiency	Mid-point E_1	$100-E_1$	Correction Factor: 98% 90% 80% Wet Scrubber (001,002,003)	Correction Factor: 85% 75% 60% Dry Cyclone (007,008, 009)	Correction Factor: 99% 95% 90% Electrostatic Precipitator (010,011,012)	C.F. Avg.
> 0 and ≤40	20	80	1.0	1.0	1.0	1
>40 and ≤60	50	50	1.25	1.8	1.5	1.52
>60 and ≤65	62.5	37.5	1.3	2.0	2.0	1.77
>65 and ≤70	67.5	32.5	1.4	2.25	2.5	2.05
>70 and ≤75	72.5	27.5	1.5	2.5	2.7	2.3
>75 and ≤80	77.5	22.5	1.6	3.0	2.8	2.46
>80 and ≤83	81.5	18.5	1.8	3.0	2.8	2.53
>83 and ≤86	84.5	15.5	2.0	3.5	3.0	2.83
>86 and ≤89	87.5	12.5	2.0	3.5	3.5	3.0
>89 and ≤91	90.0	10.0	2.5	4.0	4.0	3.5
>91 and ≤93	91.5	8.5	3.0	4.0	4.5	3.8
>93 and ≤95	94	6	4.0	4.0	5.0	4.3
>95 and ≤97	96	4	5.0	4.0	5.0	4.6
>97 and ≤99	98	2	5.0	4.5	5.5	5.0
>99 and ≤100	99.5	0.5	5.0	5.0	6.0	5.3

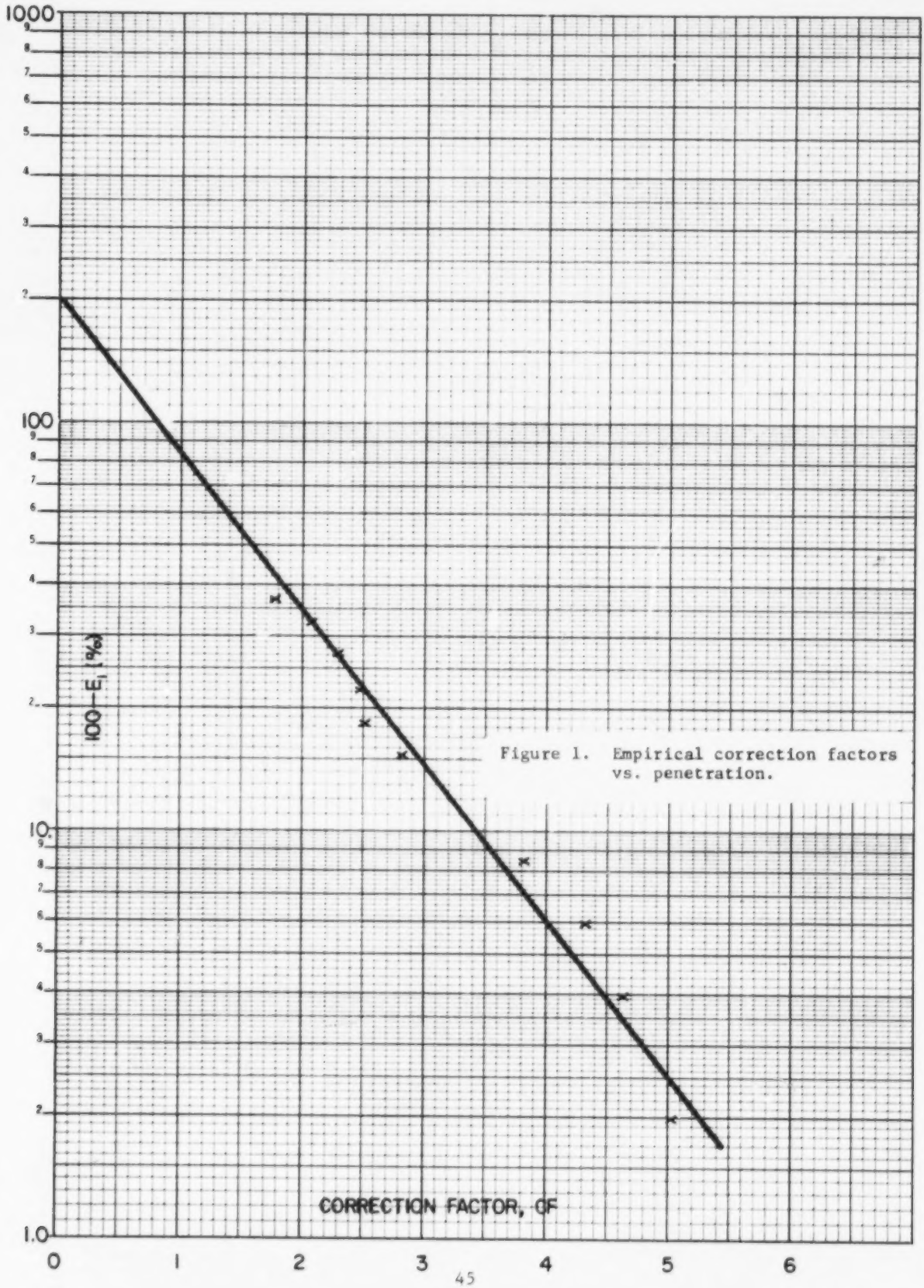

Figure 1. Empirical correction factors vs. penetration.

Table 5. Tandem efficiencies by empirical method

			SECONDARY DEVICE																
Device Number			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Rated Efficiency, E_2			98	90	80				85	75	60	99	95	90	80	99	85	99	99	99
PRIMARY DEVICE	1																			
	2																			
	3																			
	4	60	98.5	92.3	84.6				88.5	80.3	69.3	99.2	96.2	92.3	84.6					
	5	40	98.3	91.3	82.8				87.1	78.5	65.5	99.1	95.7	91.4	82.8					
	6	30	98.2	81.2	82.5				86.9	78.1	65	99.1	95.6	91.2	82.5					
	7	85	99.1	95.4	90.7				93	88.4	81.5	99.5	97.7	95.4	90.7			99.5	99.5	99.5
	8	75	98.8	93.8	87.6				90.7	84.5	75.2	99.3	96.9	93.8	87.6			99.3	99.3	99.3
	9	60	98.5	92.3	84.6				88.5	80.8	69.3	99.2	96.2	92.3	84.6			99.2	99.2	99.2
	Device Number	Rated Efficiency, E_1																		

$$\text{Overall Efficiency, EOA} = 1 - \left[(1-E_1)\left|\frac{0.3010 - \log_{10}(1-E_1)}{0.3642}\right|^{(1-E_2)}\right] \qquad (4.1\text{-}5)$$

NOTE: The rated efficiencies of primary and secondary devices shown in this table are chosen arbitrarily. The algorithm is used by entering the actual efficiencies of the device for the actual dust to be controlled.

4.2 OVERALL EFFICIENCY BY ANALYTICAL METHOD

Vatavuk[2] and Gipson[3] have demonstrated that the efficiency of a particulate collecting device relying on inertia (as cyclone, scrubber, electrostatic precipitator) can be found from the equation,

$$E = \int_0^\infty [(\beta e^{- \beta D}) (1 - e^{- \gamma D})] dD . \qquad (4.2\text{-}1)$$

where β is a parameter characterizing the frequency distribution of the dust particle sizes and γ characterizes the control device.

In deriving the expression above, it was assumed that both the frequency distribution of the dust particle size and the separation efficiency of the device can reasonably be represented by simple exponential functions. Unless the extremely large or extremely small particles are of unusually high significance, these assumptions are reasonable.

The size collecting efficiency of a device is given as Q(D), and the cumulative size distribution,

$$Y(D) = \int_{-\infty}^{D} f(D) dD . \qquad (4.2\text{-}2)$$

If we assume a log-normal distribution of particle sizes, a reasonable representation of the cumulative distribution between the 16 and 85 percentiles is an exponential of the form,

$$Y(D) = e^{- \beta D} \qquad (4.2\text{-}3)$$

where β is a parameter characteristic of a specific particle size distribution. Collection efficiency for particle size D is of the form,

$$Q(D) = 1 - e^{-\gamma D} \tag{4.2-4}$$

where γ is a parameter characteristic of a particular collecting device. Efficiency of collection then is,

$$E = \int_0^\infty f(D)Q(D)dD. \tag{4.2-5}$$

since

$$f(D) = \frac{-d}{dD}\left[Y(D)\right] = \beta e^{-\beta D}, \tag{4.2-6}$$

$$E = \int_0^\infty \left[\left(\beta e^{-\beta D}\right)\left(1 - e^{-\gamma D}\right)\right] dD \tag{4.2-7}$$

Equation 4.2-7 is useful in estimating the efficiency of a collecting device on a particular dust. The parameter, γ has been evaluated for cyclones (Gallaer); for scrubbers (Ranz and Wong); and for electrostatic precipitators (Engelbrecht) as cited by Vatavuk.[2] The dust parameter β is the slope of the straight line relating particle size to the logarithm of the cumulative distribution.

Gipson[3] points out that if the rated efficiencies E_1 and E_2 of two devices are known, the exponential parameters can be calculated, and the overall efficiency of their tandem arrangement can be determined.

For a primary device with E_1 rated efficiency,

$$\gamma_1 = \frac{\beta E_1}{1-E_1} \tag{4.2-8}$$

and for a secondary device with E_2 rated efficiency,

$$\gamma_2 = \frac{\beta E_2}{1-E_2} \cdot \tag{4.2-9}$$

The frequency distribution of the particle stream leaving the primary device (and entering the secondary), $f_2(D)$, has been modified by the removal of selected sizes by the primary device. The applied efficiency of the secondary device then is,

$$AE_2 = \int_0^\infty f_2(D)\ Q_2(D)\ d\ D. \tag{4.2-10}$$

By means of a differential mass balance over the two tandem devices, $f_2(D)$ is found to be,

$$f_2(D) = \left(\frac{\beta}{1 - E_1}\right) \exp\ \left(- \frac{\beta}{1 - E_1}\right) D \tag{4.2-11}$$

Since $Q_2(D) = 1 - \exp\left(- \frac{\beta E_2}{1 - E_1}\right) D$, the applied efficiency of the secondary device is

$$AE_2 = \int_0^\infty \left[\left(\frac{\beta}{1 - E_1} \right) \exp\left(- \frac{\beta}{1 - E_1} \right) D \right] \left[1 - \exp\ \left(- \frac{\beta E_2}{1 - E_2} \right) D \right] dD = \frac{E_2(1 - E_1)}{1 - E_1 E_2}$$

$$= \frac{E_2(1 - E_1)}{1 - E_1 E_2} \tag{4.2-12}$$

Since the overall efficiency of tandem devices is (from eq. 4.1-2),

$$EOA = 1 - (1 - E_1)(1 - AE_2),$$

then

$$EOA = \frac{E_1 - 2E_1E_2 + E_2}{1 - E_1E_2} \qquad (4.2\text{-}13)$$

This equation was programmed to generate a matrix of primary and secondary efficiencies to yield overall efficiencies (see table 6).

Table 6. Tandem efficiencies by analytical method

			SECONDARY DEVICE																	
Device Number			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Rated Efficiency, E_2			98	90	80				85	75	60	99	95	90	80	99	85	99	99	99
PRIMARY DEVICE	1																			
	2																			
	3																			
	4	60	98	91.3	84.6				87.7	81.8	75	99	95.3	91.3	84.6					
	5	40	98	90.6	82				86.4	78.6	68.4	99	95.2	90.6	82.4					
	6	30	98	90.6	81.6				85.9	77.4	65.8	99	95	90.4	81.6					
	7	85	98.2	93.6	90.6				91.9	89.6	87.8	99	96.1	93.6	90.8			99	99	99
	8	75	98.1	92.3	82.5				89.6	85.7	81.8	99	95.7	92.3	87.5			99	99	99
	9	60	98	91.3	84.6				87.8	81.5	75	99	95.3	91.3	84.5			99	99	99
	Device Number	Rated Efficiency, E_1																		

$$\text{Overall Efficiency, EOA} = \frac{E_1 - 2E_1 \times E_2 + E_2}{1 - E_1 \times E_2} \qquad (4.2\text{-}13)$$

NOTE: The rated efficiencies, of the primary and secondary devices shown in this table, are chosen arbitrarily.
The algorithm is entered with the actual efficiencies of the devices on the actual dusts to be controlled.

4.3 TANDEM EFFICIENCY ALGORITHMS - COMPARISON

(1) $$EOA = \frac{E_1 - 2E_1 \times E_2 + E_2}{1 - E_1 \times E_2} \qquad (4.2\text{-}13)$$

(2) $$EOA = \left[1 - (1 - E_1)^{\left|\frac{0.3010 - \log_{10}(1 - E_1)}{0.3642}\right|}(1 - E_2)\right]. \qquad (4.1\text{-}5)$$

Algorithm (1) is based on an exponential distribution of particle size. Algorithm (2) was developed from the particle size distribution of a "standard silica dust",[1] but is reasonably applicable to other distributions.

The above methods give results of overall efficiency within ½ to 1½ percent of each other, method (2) being higher. Method (1), however, is simpler to work with in calculator computations and gives results well within the accuracy of the basic data on device efficiency.

With a primary device having a rated efficiency of 90 percent, followed by secondary devices in tandem of efficiencies 90 percent, 95 percent, and 99 percent a comparison of overall efficiencies (EOA) by the two methods shows:

E_1	E_2	EOA Method(1)	EOA Method(2)
90	90	94.7	96.4
90	95	96.5	98.2
90	99	99.08	99.64

4.4 CALCULATION FROM EXPERIMENTAL DATA

Although algorithms (1) and (2) were based respectively on an exponential particle size distribution and "the standard silica dust", they give fairly accurate results of overall efficiency provided the primary and secondary stand-alone efficiencies are empirically determined. It is well recognized, however, that dust distributions actually are best represented by the log-normal.[4]

Reasonable estimates for the efficiency of a device in the collection of a real dust can be made if the geometric mean and standard geometric standard deviation of the dust particle size are known.[5] If, in addition, the fractional efficiency[6] of the collecting device has been determined, the stand-alone efficiency of the device can be computed as it pertains to the known dust.

4.4.1 Graphical Method

Example A.

For this example, an asphalt plant dryer dust was selected with geometric standard deviation, S_g, of

$$\frac{50 \text{ percentile}}{16 \text{ percentile}} = \frac{18\mu m}{3.4\ \mu m} = 5.29$$

The primary collecting device is a medium-efficiency cyclone followed by a low-energy wet scrubber as secondary collector.

The 50-percent and 16-percent cumulative particle loading of the dust will establish two points of a straight line on log-probability coordinates (see figure 2A). Fractional efficiency curves for the two selected devices are shown in figure 3A.

The treatment shown in table 7A illustrates the method of applying fractional efficiency data of a dust collecting device to a known dust

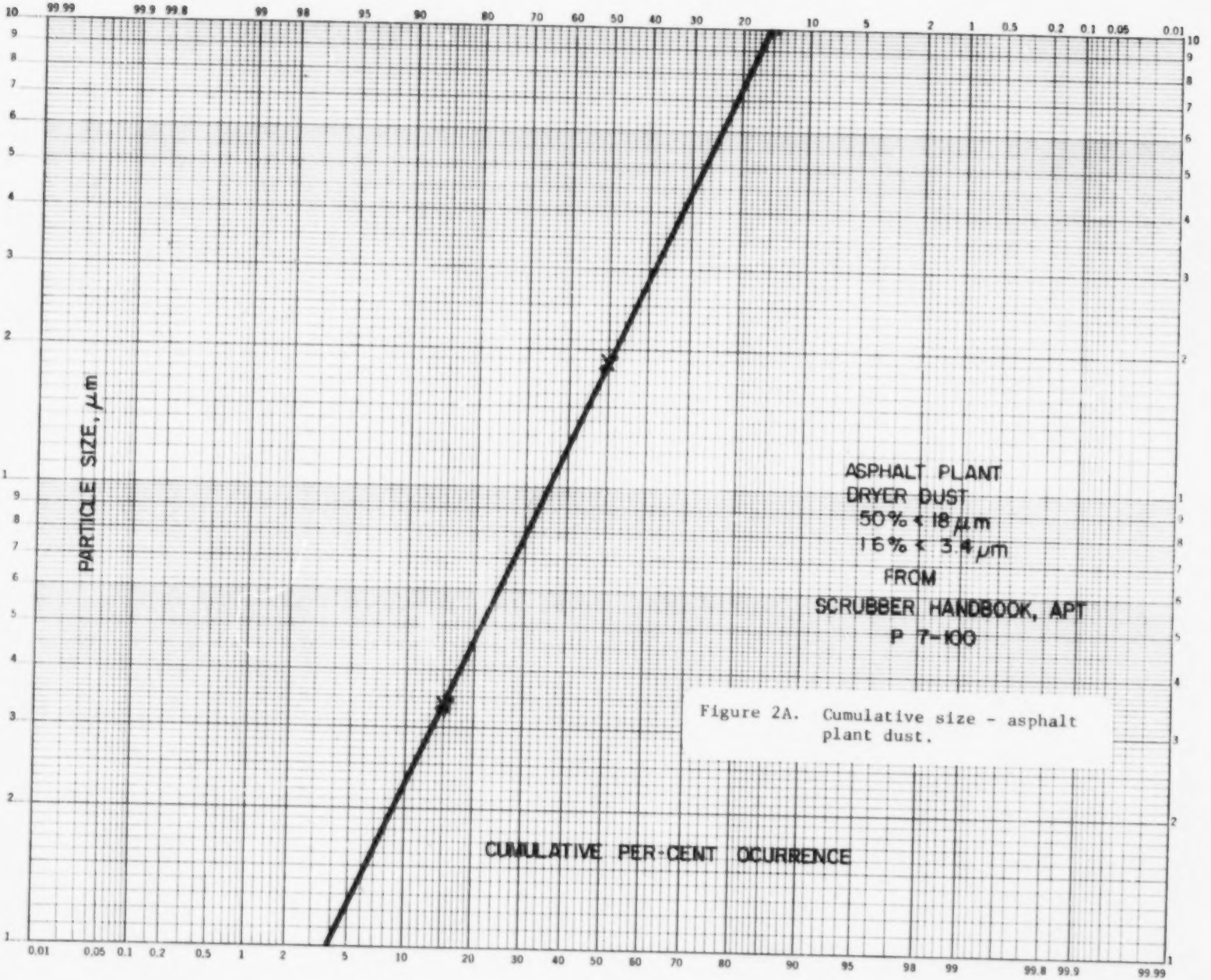

Figure 2A. Cumulative size - asphalt plant dust.

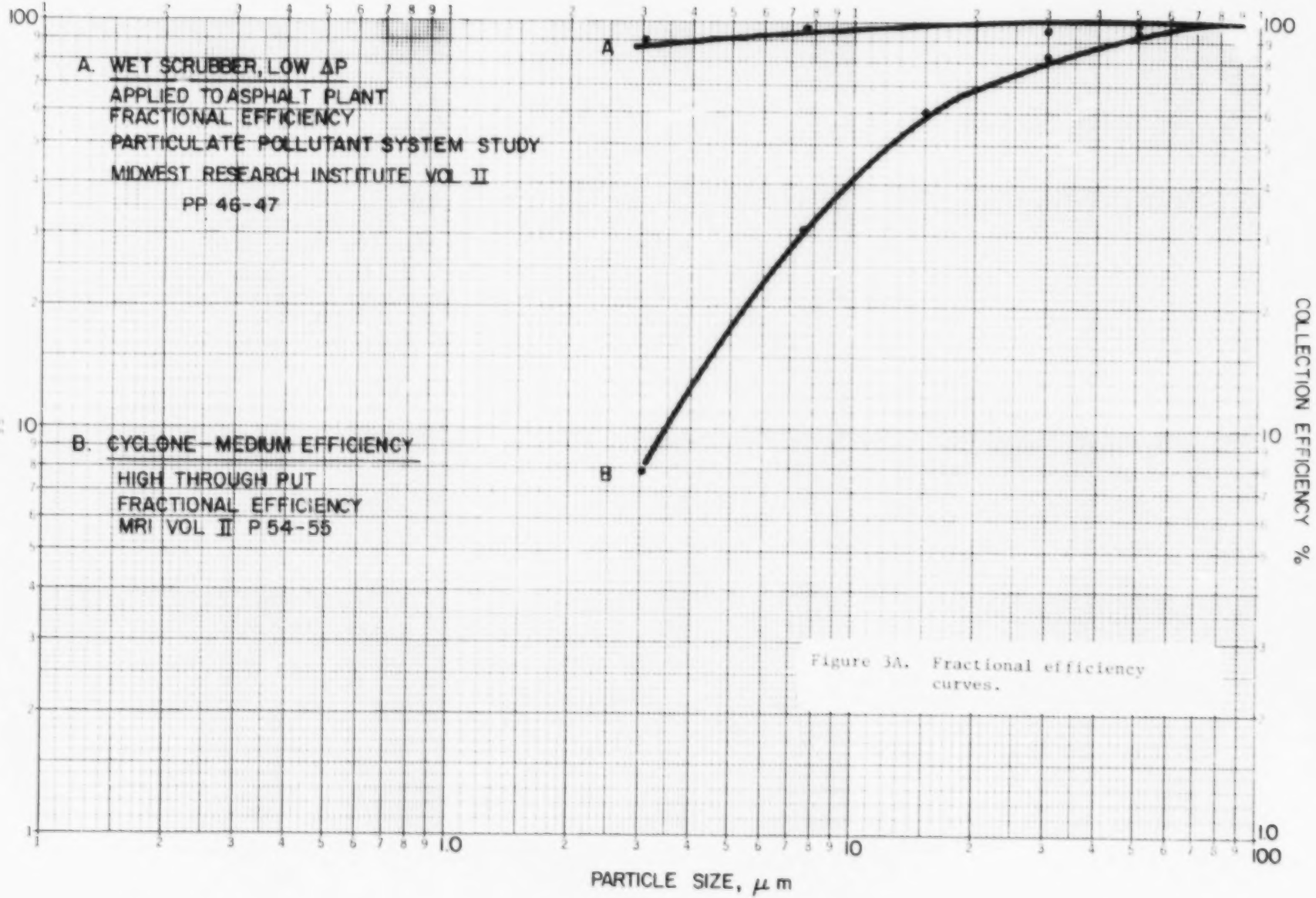

Figure 3A. Fractional efficiency curves.

Table 7A. Efficiency calculations - comparison of algorithms

Example A

Size range	Accum. in Range	Percent in range	Size Midpoint	Fract. Eff. Venturi	Weight % retained by Venturi	Fract. Eff. Cyclone	Weight % retained by Cyclone	Passed by Cyclone (Primary)	Retained by Venturi (Secondary)
100-80	84.5-81	3.5	90 μm	100	3.5	99	3.465	0.035	0.035
80-60	81 - 76	5.0	70 μm	100	5.0	97	4.85	0.15	0.15
60-40	76 - 68	8.0	50 μm	99	7.92	94	7.52	0.48	0.475
40-20	68 - 52	16.0	30 μm	97.5	15.6	80	12.8	3.2	3.2
20-10	52 - 37	15.0	15 μm	97.0	14.55	60	9.0	6.0	5.82
10-5	37 - 22	15.0	7.5 μm	96.0	14.4	30	4.5	10.5	10.08
5-1	22 - 4	18.0	3 μm	88.0	15.84	8	1.44	16.56	14.57
		80.5			76.81		43.58	36.925	34.25

Stand-alone efficiency of Venturi = 78.81/80.5 = 95.4 %
Stand-alone efficiency of cyclone = 43.58/80.5 = 54%
Total dust retained by both units in tandem = 43.58 + 34.25 = 77.83
Overall efficiency of tandem units = 77.83/80.5 = 96.68%

In tandem, E_1 = 54%, E_2 = 95.4%
By algorithm (1)

(4.2-13) $$EOA = \frac{E_1 - 2E_1 \times E_2 + E_2}{1 - E_1 \times E_2} = \frac{0.54 - 2 \times 0.54 \times 0.954 + 0.954}{1 - 0.54 \times 0.954} = \frac{0.464}{0.485} = 95.6\%$$

By algorithm (2)

(4.1-5) $$EOA = 1 - (1 - E_1)\left[\frac{0.3010 - \log_{10}(1-E_1)}{0.3642}\right](1-E_2) = 1 - 0.46\left[\frac{0.3010 + 0.3826}{0.3642}\right]0.046 = 96.03\%$$

for which we know the geometric mean particle size and the geometric standard deviation. Thus, for the selected dust, the cyclone is found to have a stand-alone efficiency E_1, of 54 percent, and the venturi E_2 = 95.4 percent. If these stand-alone efficiencies are already known, however, use of the tandem efficiency algorithms are useful in estimating overall efficiency of particulate control. Algorithm (2) agrees with the tabular calculations of the overall efficiency of 96.68 percent within 0.7 percent. Algorithm (1) comes within 1.1 percent. Either model is well within the reliability of the basic data. The range of data reported in the literature for efficiency of particular control devices and on the composition of particular dust emissions is quite wide, and percentage-wise exceeds the deviations found above for estimating tandem efficiencies by either of the two models suggested.

Example B

For this example, we select a dust with less dispersion of particle size, namely a steel making open hearth off-gas using oxygen lancing. From table 7.2-19, in the Scrubber Handbook, A.P.T., Inc., we find,

$$S_g = \frac{50 \text{ percentile}}{16 \text{ percentile}} = \frac{6}{1.7} = 3.529$$

This dust is less disperse than the asphalt dryer dust in Example A, for which

$$S_g = 5.29.$$

Primary collector is a 12" diagonal cyclone, 610 ft^3/min, 7" H_2O ΔP. Fractional efficiency curve for this device is shown on figure 3B. Data are taken from Particulate Pollutant Study, Midwest Research Institute, Vol. II, figure 13.[5]

The secondary is a venturi scrubber, throat velocity 17,800 ft^3/min. Fractional efficiency is from figure 11 of the Midwest Study.

Plotting the 50 percentile and 16 percentile sizes on log-probability coordinates for the open hearth dust on figure 2B yields a straight line from which class size cumulative probabilities can be read.

Table 7B develops the stand-alone and tandem efficiencies of the selected devices. Algorithms (1) and (2) estimate the tandem efficiency within 0.7 percent and 0.2 percent respectively of the tabular calculation for overall efficiency.

The stand-alone efficiency of this venturi is calculated on table 7B as 96.6 percent using dust characteristics and fractional efficiencies given above. Venturi efficiencies on open hearth off-gases range from 98.2 percent to 99.6 percent, as reported on page 7-41 of the Scrubber Handbook. Comparison is not possible, however, since there is no information on the relative power inputs to the scrubbers (see section 5.1).

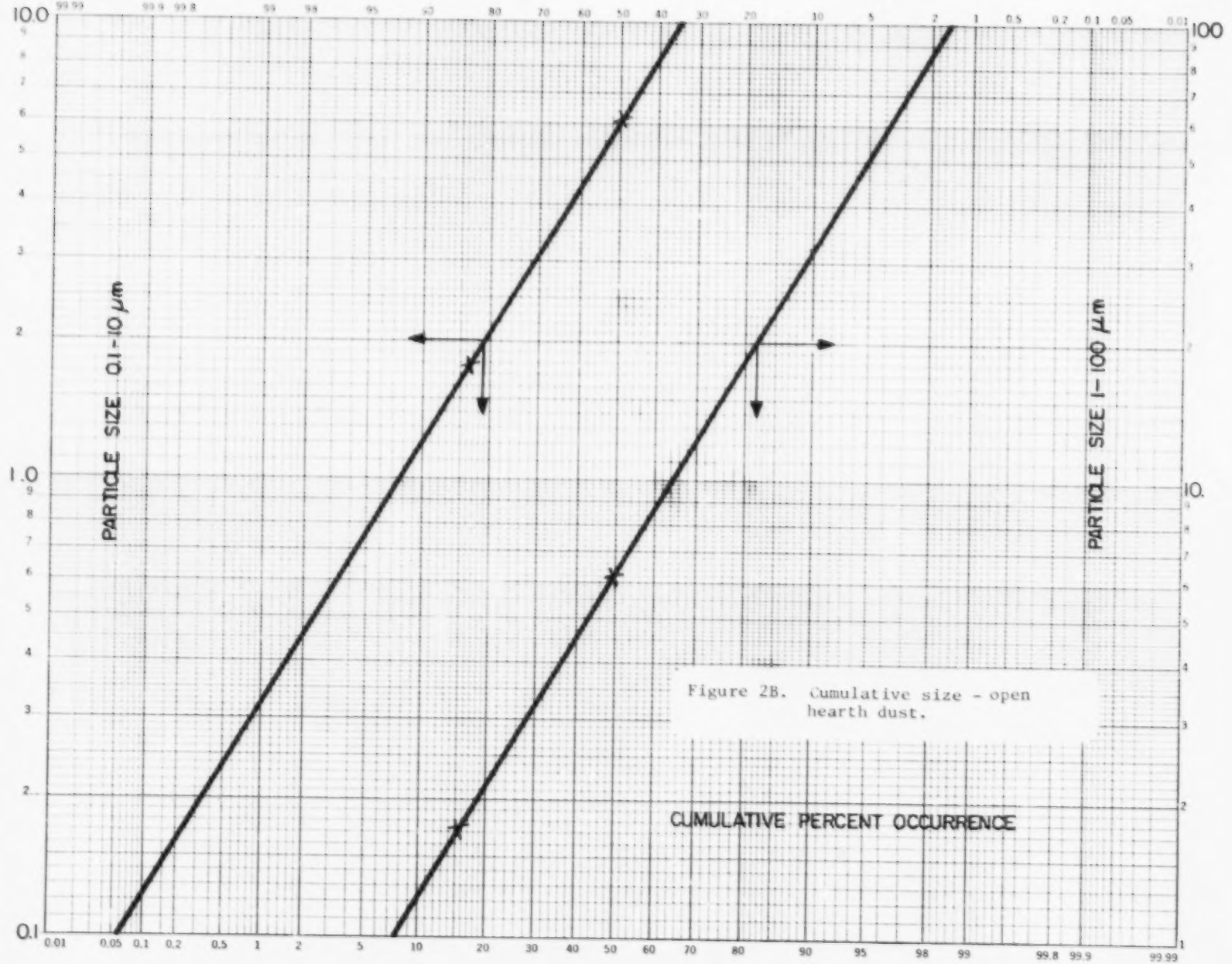

Figure 2B. Cumulative size - open hearth dust.

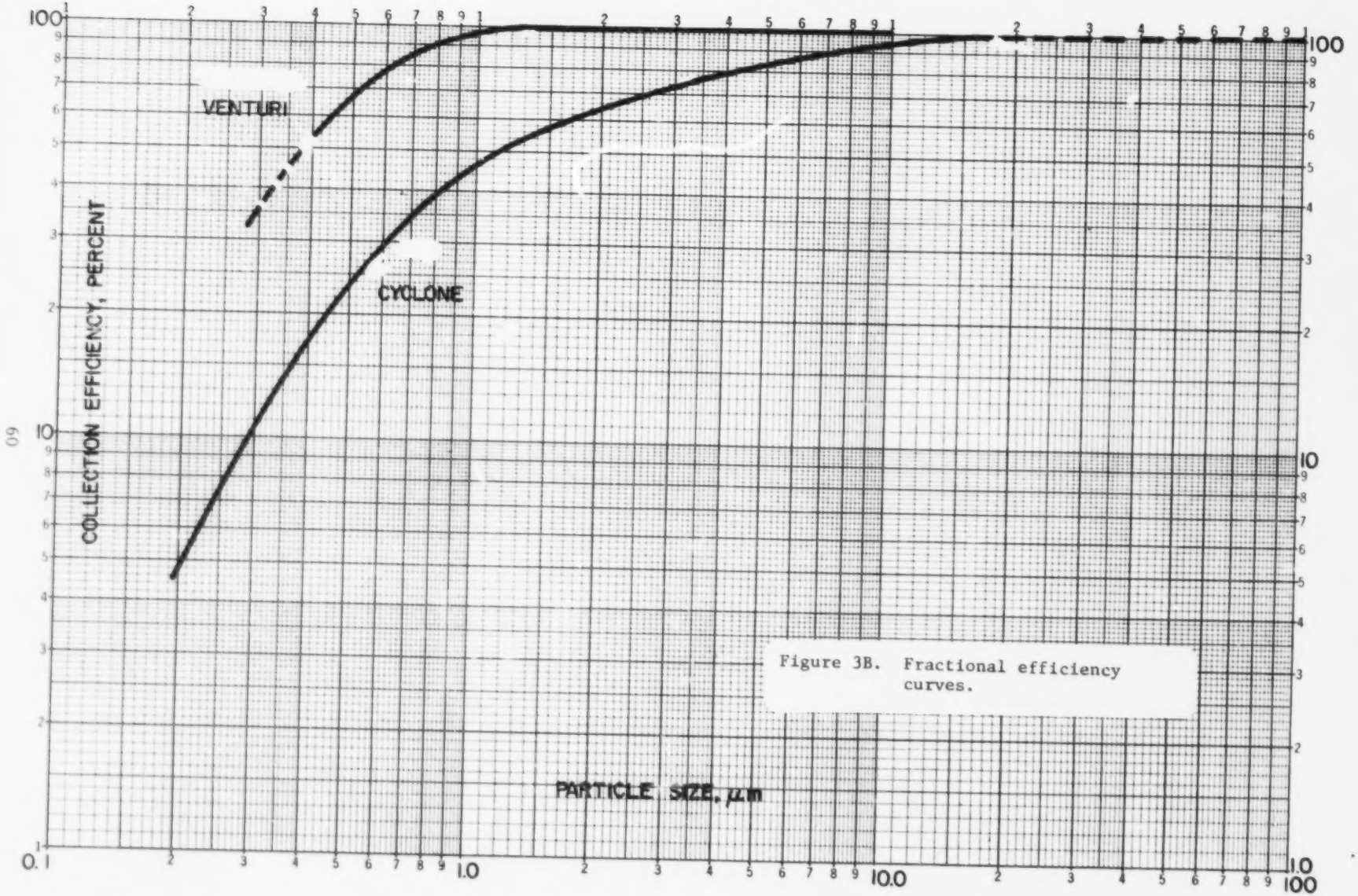

Figure 3B. Fractional efficiency curves.

Table 7B. Efficiency calculations - comparison of algorithms

Example B

Size Range	Accum. in Range	Percent in range	Size Midpoint	Fractional Efficiency Cyclone	Weight % Retained by Cyclone	Passed by cyclone (Primary)	Fractional Efficiency Venturi	Retained by Venturi (Secondary)	Retained by Venturi as a Primary
100-80	98.6-98	0.6	90	100	0.6	0	100	0	0.6
80-60	98 -96.5	1.5	70	100	1.5	0	100	0	1.5
60-40	96.5-93	3.5	50	99	3.465	0.035	100	0.035	3.5
40-20	93 -83	10	30	96	9.6	0.04	100	0.04	10.0
20-10	83 -68	15	15	92	13.8	1.2	100	1.2	15.0
10- 5	68 -44	24	7.5	85	20.4	3.6	99	3.564	23.76
5-1	44 - 8	36	3.0	70	25.2	10.835	98	10.618	35.28
1- .5	8 - 2.5	5.5	0.75	37	2.035	3.465	86	2.980	4.73
.5- .1	1.5- 0.06	2.44	0.30	10	0.0244	2.416	35	0.846	0.854
		98.54			76.6244	21.951		19.643	95.224

Stand-alone efficiency of cyclone, $E_1 = \frac{76.6244}{98.54} = 77.8\%$

Stand-alone efficiency of venturi, $E_2 = \frac{95.224}{98.54} = 96.6\%$

Total dust retained by both units in tandem = 76.6244 + 19.643 = 96.2674

Overall efficiency of tandem units EOA = $\frac{96.2674}{98.54} = 97.7\%$

In tandem E_1, = 0.778, E_2 = 0.966

By algorithm(1)
(4.2-13) $$EOA = \frac{E_1 - 2E_1 \times E_2 + E_2}{1 - E_1 E_2} = \frac{0.778 - 2 \times 0.778 \times 0.966 + 0.966}{1 - 0.778 \times 0.966} = \frac{1.744 - 1.503}{0.2484} = 97.02\%$$

By algorithm(2)
(4.1-5) $$EOA = 1-(1-E_1)\left[\frac{0.3010-\log_{10}(1-E_1)}{0.3642}\right](1-E_2) = 1-0.222\left[\frac{0.3010 + 0.6941}{0.3642}\right](1-0.966) = 1-0.206 = 97.94\%$$

4.4.2 Approximate Model

Figures 2A and 2B show a graphical method of displaying the particle size distribution of a dust for which the geometric mean size and the standard geometric deviation are known. Particle size parameters for a number of industrial dust streams are given in the literature (see Scrubber Handbook, Vol.I, A.P.T., 1972). From the 50 percentile and the 16 percentile cumulative size data, we find the geometric mean, M_g at the 50 percentile size. The deviation is the ratio,

$$S_g = \frac{\text{size at 50 \%}}{\text{size at 16 \%}}$$

The size of a particle, D, can be found from,[7]

$$D = M_g (S_g)^Z$$

where Z is the number of standard deviations on the probability curve at the percentile where the size, D, is required. The values of Z can be found from statistical tables (Pearson and Hartley, 1966). The value of Z is plotted against percentile in figure 4, and faired to yield the equation,

$$Z = 0.03016(\text{Per}) - 1.5$$

$$D = M_g (S_g)^{0.03016(\text{Per})-1.5}$$

Per = percentile corresponding to "D"

$$= \frac{\log \frac{D}{M_g}}{0.03016 \log S_g} + 49.73$$

The above relationships are fairly accurate between the values of percentile from Per = 10 percent to Per = 90 and may be useful for manual calculations within this range.

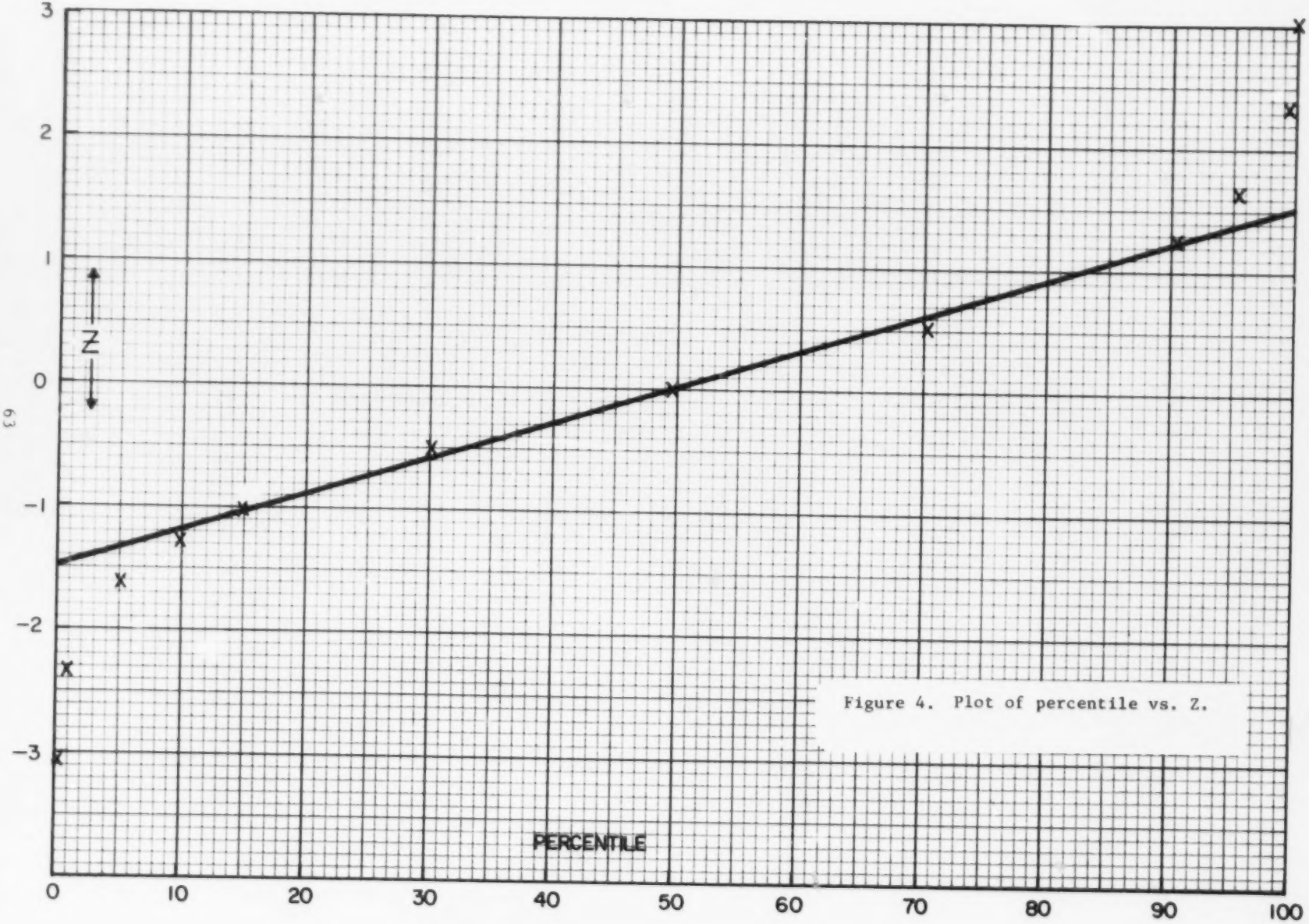

Figure 4. Plot of percentile vs. Z.

4.4.3 Analytical Method

A more precise relationship, suitable for computer programming, is developed below.[7]

a) Given M_g and S_g to find particle size, D, corresponding to a cumulative percentile, Per:

$$1)\quad D = M_g(S_g)^Z$$

$$2)\quad Z = \eta - \frac{2.30753 + (0.27061)\eta}{1 + (0.99229)\eta + (0.04481)\eta^2}$$

where $\eta = \sqrt{\ln\left(\frac{1}{p^2}\right)}$

and $p = \begin{cases} 1 - \frac{Per}{100} & \text{if } 50\% < Per \\ \frac{Per}{100} & \text{if } Per < 50\% \end{cases}$

if Per < 50 - Z from (2) is applied in (1)

if Per > 50 + Z from (2) is applied in (1)

b) To find the percentile, Per, given the size, D, of the particle:

First, compute:

$$x = \frac{\ln D - \ln(M_g)}{(1.414)\ \ln(S_g)}$$

i) if $x < 0$, take the absolute value of x and use the following formula[7],

$$A = 1 - \frac{1}{\left[1 + (0.27893)\,x + (0.23089)\,x^2 + (0.000972)\,x^3 + (0.078108)\,x^4\right]^4}$$

Then,

$$Per = 0.5 - \frac{A}{2}$$

ii) if $x > 0$, put x, as is, in the above formula to get A.

Then,

$$Per = 0.5 + \frac{A}{2}$$

As an example, from figure 2A, we find the size D, below which 70 percent of the particles occur, to be 43 μm.

For this dust $M_g = 18$

$$S_g = 18/3.4 = 5.29.$$

From paragraph 4.4.3.a).1)

$$D = M_g (S_g)^Z \qquad (1)$$

$$Per = 70\ \% = 0.70$$

$$p = 1 - Per = 0.30$$

$$n = \sqrt{\ln\left(\frac{1}{p^2}\right)} = \sqrt{\ln\left(\frac{1}{(0.3)^2}\right)} = 1.55176$$

$$Z = 1.55176 - \left[\frac{2.30753 + (0.27061)(1.55176)}{1 + (0.99229)(1.55176) + (0.04481)(1.55176)^2}\right]$$

$$= 1.55176 - 1.03012 = 0.52164.$$

Since Per > 50

$$D = 18(5.29)^{0.52} = (18)(2.38) = 43\ \mu m.$$

This example of the analytical procedure checks the graphical display of the cumulative distribution of particle sizes, and suggests the possibility of using computer techniques for applying fractional efficiencies to particle sizes that are log-normally distributed. When stand-alone efficiencies of tandem units are found, the algorithms from section 4.3 can be entered to compute tandem efficiencies.

4.4.4 Characterizing Dust

The advantages of determining and reporting dust parameters as the 50 and 16 cumulative percentile sizes are:

a) the ability to establish a linear relationship between size and cumulative percent occurrence,

b) facility for interpolating data,

c) ability to extrapolate data with some reservations.

The 50 and 16 percentile particle sizes for a number of industrial dusts are tabulated in section 7 of the Scrubber Handbook, A.P.T., Inc., August 1972. From these parameters, the dispersion of the distribution, or, the standard geometric deviation S_g can be calculated as the ratio of the size at the 50 percentile to the size at the 16 percentile points.

A selection of these data is given in table 8.

Table 8. Selected dusts - size parameters

Dust	Particle Size, μm under 16%	Particle Size, μm under 50%	S_g
Coal Dryer, Fluidized Bed	45	200	4.44
Coal Dryer, Multilouver	6.6	28	4.24
Coal Dryer, Cascade	6.6	28	4.24
Stone, Jaw Crusher	20	200	10.0
Lime Calcining, Rotary Kiln	3.5	50	14.3
Lime Calcining, Vertical Kiln	13	30	2.3
Coal Combustion, Cyclone Furnace	1.85	6.4	3.46
Coal Combustion, Pulverized Coal	6	18	3.0
Coal Combustion, Spreader Stoker	14	58	4.14
Coal Combustion, Underfeed Stoker	21	100	4.76
Steel, Open Hearth, with Oxygen Lance	1.7	6	3.5
Steel, Basic Oxygen Furnace	0.041	0.095	2.3
Cupola Furnace	7	100	14.3
Ferroalloy, Blast Furnace	0.1	0.45	4.5
Ferroalloy, Electric Furnace	0.1	0.3	3.0
Kraft Pulp, Recovery Furnace	0.48	1.0	2.1
Phosphate Fertilizer, Rotary Dryer	13	80	6.2
Asphalt Pavement Batching, Rotary Dryer	3.4	18	5.3
Incinerator, Municipal	1.6	90	56.3

5.0 DEVICE EFFICIENCY

A literature search was made to determine the actual equipment used in the many industrial processes for control of particulate and SO_x pollutants. The collection of these data, as detailed in section 3, gives an overall view of current practice and performance (see table 3).

5.1 MECHANICAL DEVICES - EFFICIENCY

It was found that literature references often give a range of efficiency with a particular device class and in the same SIC process category. Variation also existed among the various literature sources.

Collection efficiency is not a property inherent with a particular device class. Weight fraction of a dust collected by a particular device depends not only on the performance of the equipment but also on the nature of the dust, i.e., particle size distribution, chemical and physical properties of the particles, etc. Energy input to the collector is of primary importance in determining efficiency.

As an example, the particle size is given below for particles collected with identical efficiency, 98.5 percent, by venturi scrubbers of different energy inputs:[8]

Δ P, "H_2O	Particle Size, µm
5"	10
10"	3.7
20"	1.3
30"	0.64
40"	0.40

Another way to show this is to select a fixed particle size, say 1 µm, and give the pressure drop and the collection efficiency at that pressure drop.

Δ P, "H_2O	Efficiency, %
5"	81
10"	93
20"	98
30"	98.6
40"	99.7

Semrau has correlated scrubber efficiencies by means of the model,[9]

$$\eta = 1 - \exp(-\alpha P^{\gamma}) \qquad (5.1\text{-}1)$$

where η is efficiency of collection, α and γ are dust parameters related to size and distribution, and P is total contacting power.

Some representative dust parameters are:

Talc dust	Venturi $\alpha = 0.915$	$\gamma = 1.05$
Foundry Cupola	Venturi $\alpha = 1.35$	$\gamma = 0.621$
Open Hearth	Venturi $\alpha = 1.26$	$\gamma = 0.569$

To determine collection efficiency, we would need to know the total contacting power, P, in horsepower per 1000 ft^3/min of gas. Once the dust parameters α and γ are established empirically, it is possible to predict the performance of the particular type of scrubber by prescribing the required hydraulic and pneumatic power input to the contactor.

5.2 ELECTROSTATIC PRECIPITATORS (ESP) - EFFICIENCY

The Deutsch-Anderson equation for ESP efficiency is:

$$\eta = 1 - \exp\left(-\frac{A}{V_g} w\right) \qquad (5.2\text{-}1)$$

A = area of collecting surface, ft^2

V_g = gas flow rate, ft^3/min

w = precipitation rate parameter, ft/min

Average values of the precipitation rate parameters, w, and the efficiency of collection of particulates in offgases are given for the following industries.[10]

w, ft/min	Industry	Efficiency, at $A/V_g = 0.120$	Efficiency, at $A/V_g = 0.300$
3.6	Smelter	35%	66%
6.0	Cupola	51%	80.9%
9.6	Open Hearth	68%	94.4%
14.4	Sulfuric Acid	82%	98.67%
15.0	Pulp and Paper	83.5%	98.89%
21.0	Cement	92.0%	99.82%
21.6	Blast Furnace	92.5%	99.85%
25.8	Utility Fly Ash	95.5%	99.98%

The sulfur content in the fuel exerts a large effect on the efficiency of collection of fly ash from a pulverized coal utility boiler furnace.

The influence of the fuel sulfur content on w, the precipitation rate, is shown as follows:[11]

% S	w, ft/min	Efficiency
1	17.22	$1 - \exp(-17.22\ A.V_g)$
2	43.67	$1 - \exp(-43.67\ A/V_g)$
3	75.07	$1 - \exp(-75.04\ A/V_g)$

For a boiler with inlet temperature of 300°F to the ESP and $A/V_g = 0.120$,

% S	η
0.5	74%
1.0	78%
1.5	81%
2.0	84%
2.5	92%
3.0	99%

The above data can be represented by,

$$\log \eta = 0.0478\ S + 1.8388 \quad (\text{for } A/V_g = 0.120) \tag{5.2-2}$$

The interrelationship between device and dust characteristics, discussed in section 5.1 above, is even more vividly shown in the case of ESP's where the electrical properties of the dust affect the collection efficiency drastically. The precipitation rate as a function of dust particle size and resistivity can vary as much as 8 to 1 in various dusts with efficiencies of collection varying as much as 2 to 1 in the same size ESP with identical gas volume flow rate.

The efficiency of an ESP in combustion gas service is further affected by sulfur to ash ratio, power input, type of furnace, etc. An empirical model based on the Deutsch equation has been developed for a pulverized coal furnace by Selzer and Watson as follows:[12]

$$\eta = 1 - \exp\left[-0.57 \times 203\ \left(\frac{A}{V}\right)^{1.4} \times \left(\frac{kW}{v}\right)^{0.6} \times \left(\frac{S}{AH}\right)^{0.22}\right]$$

where,

A = collecting plate area (1000's of ft^2);

V = flue gas volume flow (1000's of ACFM);

kW = power input to discharge electrodes, kW;

S/AH = sulfur to ash ratio in fuel, by weight;

η = efficiency, fractional.

The number 203, applicable to a pulverized coal furnace, is replaced by 157.6 for a cyclone furnace because of the smaller sized particles in the latter, and because of the particle resistivity associated with that type of firing. The same reduction in η occurs if the ESP is preceded by a cyclone.

5.3 ADD-ON DEVICE EFFICIENCY

In addition to evaluating current pollution control levels, the IPP faces the problem of improving control in those areas or industries that are deficient. In this case there is the advantage of specifying control effectiveness of the add-on device to achieve an acceptable overall control level. In specifying the efficiency of the additional control there is considerable flexibility since efficiency levels can be built into devices within reasonable constraints of engineering and economics.

For instances of the above points, cyclones can be designed for high pressure drops at the cost of power; scrubbers can be designed with high gas and liquid energies by use of high pressure blowers and pumps; electrostatic precipitators can be made with longer residence time by adjustment of contact area or gas velocity; fabric filters are inherently high efficiency devices, but need design ingenuity to adapt them to temperature, corrosion, and abrasion forces.

If the actual existing collection efficiency, E_1, of a particular process control device is known, a secondary device with a design efficiency, E_2, can be specified and designed to achieve a desired overall efficiency, EOA, by application of the estimating methods outlined in section 4.0.

6.0 IMPLEMENTATION PLANNING PROGRAM PARTICULATE CONTROL SYSTEM COSTS[13-22]

6.1 DISCUSSION AND BASIS FOR EQUATIONS

6.1.1 Capital Costs

A review of the costing procedure for particulate removal devices adopted in the original Implementation Planning Program (IPP) which establishes a "flange to flange" cost for the control device itself, and then factors this value to obtain a total installed cost, indicates that the resulting capital costs obtained tend to be significantly lower than those reported for "real-life" installations. A systems study of wet scrubbers conducted by Ambient Purification Technology, Inc., for EPA provides a direct comparison of actual installed costs for various industrial wet scrubber systems versus the high and low range of installed costs for these systems predicted by the "flange to flange" approach detailed in the NAPCA (1969) AP-51 report and followed by the IPP program. Actual costs of all types of scrubbers except packed bed scrubbers, are greater than even the predicted high range cost.

An examination of commonly accepted methods for developing preliminary capital cost estimates confirms that equipment cost is a common primary cost element but that this term includes all identifiable equipment within a system, i.e., pumps, heat exchangers, fans, etc., as well as the primary equipment. The cost of this total grouping is then factored,

depending on process characteristics, to provide associated direct material such as piping, instruments, electrical, etc. Labor to install the equipment and erect the field materials is usually determined from established labor/material relationships. Indirect costs, field supervision, engineering and contractor's fee, etc., are added as factors of the total of the foregoing. Total installed costs for a given process may run 3-4 times the total equipment cost for the usual materials of construction. Estimates made in this manner reflect considerable experience and judgment in the selection of the factors used.

Although the original IPP approach equated efficiency of the control device with total installed cost, an examination of estimates and reported costs for the installation of pollution control equipment suggests that rated efficiency of the prime device is not necessarily the determinant of the total cost, although it does influence directly the annual operating and maintenance costs. What does appear to be more important is the nature or characteristics of the source and the complexity of the installation itself. Retrofitting control equipment to an existing plant is frequently a major problem and a contributor to abnormal costs irrespective of the rated efficiency.

The uncertainties associated with both the above method of capital cost determination, and the efficiency-cost relationship have suggested an approach that establishes capital costs versus gas volume throughput for a specific control device system based on reported costs for commercial installations of that system. Total installed costs for each of the particulate control devices culled from reports identified in the references, miscellaneous articles in a variety of technical journals, and cost data extracted and synthesized from engineering studies on pollution control

systems in a number of industries, were updated to a 1974 cost basis using Marshall and Swift indices, and plotted against actual gas flow (ACFM) on log-log graph paper. These plotted costs for each control device were grouped into three cost levels--high, intermediate, low, or where more appropriate, two levels--high and low, and curves drawn through the respective groupings. Because of the data scatter and uncertain reliability, formal curve fitting techniques were not used. These cost curves were then expressed as equations of the form $y = a + bx$ to express cost versus capacity relationships.

An example of the approach taken for wet scrubbers is provided in Appendix I, Chart 1. Charts 2 - 6 provide the developed curves only, for the other specified particulate control devices.

It should be noted that in the case of electrostatic precipitators, efficiency has been retained to differentiate cost level because of the unique relationship between efficiency, the number of collecting plates in the ESP, and the plate area or size, and the direct impact of these parameters on total cost.

Each SIC source and its associated processes was then reviewed, and on the basis of the characteristics of each process--for example, corrosiveness, gas temperatures, complexity of the plant itself--each process was related to one of the available cost equations for each specific control device by an appropriate coding designation. Thus, the capital cost for particulate control devices is a direct function of the type of control device and the size or gas volume throughput and is indirectly related to the characteristics of the source itself. Section 6.2 provides coded capital cost equations. The Device Matrix, table 3 relates

the SIC number, process number, applicable control devices, and efficiencies for that process, with the associated capital cost code designation.

6.1.2 Annual Operating and Maintenance Expenses

Operating costs for particulate control devices are determined from:

a) the amount of power necessary to maintain the effluent gas flow through the control device,

b) the amount of power necessary to drive the pumps and auxiliary equipment associated with the control device,

c) the cost of water, chemicals, and additional fuel required by the system,

d) the labor required to operate the system,

e) the necessary maintenance and supplies to keep the equipment functioning at the design or operating level,

f) the cost or credit resulting from the disposal of the collected pollutants,

g) the cost of taxes and insurance and the appropriate unit costs for each of these elements. Section 6.3 provides the resulting equations for total annual operating costs for the different particulate control devices.

Not all elements are associated with each control device, but the computation of the annual usage of each of these elements is as follows:

a) Power

For all devices, the power used is a direct function of the gas throughput (ACFM) and the pressure drop (P) of the control device. The equation providing annual power requirements in kWh is developed as follows:

Pressure drop of control device = P (inches water),

Gas flow at temperature °F = ACFM;

then,

Gas flow at standard conditions (60°F and 29.92 in. Hg)

$$= \text{ACFM} \times \frac{520}{460 + T^{\circ}F}.$$

Density of air at 60°F and 29.92 in. Hg = 0.0763 lb/ft^3,

Density of water at 60°F = 62.4 lb/ft^3;

then,

$$\text{Pressure drop of device in feet of air} = \frac{(P)\ 62.4}{12 \times 0.0763} = 68.152(P)\text{feet}.$$

$$\text{Work performed} = \text{ACFM} \times \left(\frac{520}{460 + T^{\circ}F}\right) (0.0763) \times 68.152\ (P)$$

but,

33,000 ft-lbs/min = 1 HP

and

1 HP = 0.746 kW

then, if fan efficiency = 60%

$$\text{kW} = \text{ACFM} \times \left(\frac{520}{460 + T^{\circ}F}\right) \frac{(0.0763)(68.152)(P)(0.746)}{(33{,}000)(0.6)}$$

$$= \text{ACFM} \times \left(\frac{520}{460 + T}\right) \frac{(P)}{5104}$$

then annual power requirements

$$\text{kWh/year} = \text{ACFM} \times \left(\frac{520}{460 + T}\right) \frac{(P)\ (h)}{5104}$$

where ACFM = Source effluent gas flow rate

T = Temperature ($^{\circ}F$) of gas

P = Pressure drop of control device (inches water)

h = Annual hours of operation.

For wet scrubbers, the source (ACFM) is changed by virtue of both cooling and take-up of water vapor. Assuming cooling to 130 $^{\circ}F$ the new volume becomes

$$ACFM' = \left(\frac{ACFM}{460 + T}\right)\left[552.4 + 0.289T\right] \quad \text{(see section 7.1.2)}$$

where,

T = Temperature of source effluent $^{\circ}F$

ACFM = Source effluent gas rate

and

$$\text{kWh/year} = ACFM'\left(\frac{520}{460 + 130}\right)\frac{(P)(h)}{5104}$$

$$= 0.1726 \times 10^{-3}(ACFM')(P)(h).$$

The fan is assumed to be located after the wet scrubber.

The pressure drop associated with a specific control device is in most cases a function of the efficiency of the device. The following values are representative:

	Device	Efficiency (particulate removal)	Pressure Drop (in. H_2O)
001	Scrubber	High	40"
002		Medium	20"
003		Low	5"
007	Centrifugal collector	High	5"
009		Low	3"
010	Electrostatic Precipitator	High	0.5"
011		Medium	
012		Low	
016	Fabric Filter	(High temp) > 200°F	5"
017		(Low temp) ≤ 200°F	
013	Gas Scrubber		6"
014	Mist Eliminator	High	10"
015		Low	5"
019	Afterburners (Catalytic)		8"
020	Afterburners (Catalytic and Heat Exchanger)		12"
021	Direct Flame		6"
022	Direct Flame and Heat Exchanger		12"
055	Direct Flame and Regenerative		10"

b) Auxiliaries Power

Scrubbers--If the liquor circulation rate is W gal/ACFM and the water pressure at the scrubber sprays is p lb/in^2 with a pump efficiency of 50 percent, then

if 1 lb/in.^{2} = 2.3 ft water

and 1 gal water = 8.33 lbs

work performed = (p)(2.3)(ACFM)(W)(8.33) ft-lbs/min

but 33,000ft-lb/min = 1 HP

and 1HP = 0.746 kW

then with 50% pump efficiency

$$kW = \frac{(p)(2.3)(ACFM)(W)(8.33)(0.746)}{(33,000)(0.50)}$$

$$= 0.8662 \times 10^{-3}(ACFM)(p)(W)$$

Annual power requirements

$$kWh/year = 0.8662 \times 10^{-3} (ACFM)(p)(W)(h)$$

Liquor circulation and spray pressure is related to the efficiency of the scrubber and the following relationships are representative:

	(W)Circulation Rate	(p) Spray Pressure
High Efficiency	0.025 gal/ACFM	60 psi
Medium Efficiency	0.015 gal/ACFM	40 psi
Low Efficiency	0.010 gal/ACFM	25 psi

then scrubber annual auxiliaries power requirements are:

High Efficiency	kWh/yr = 0.0013 (ACFM)(hr)
Medium Efficiency	kWh/yr = 0.00052(ACFM)(hr)
Low Efficiency	kWh/yr = 0.00022(ACFM)(hr)

Electrostatic Precipitators--The power cost for ionizing the gas and operating the dust removal gear is essentially a function of the efficiency of the unit. Typical values are:

High Efficiency	kWh/yr = 0.00040(ACFM)(hr)
Medium Efficiency	kWh/yr = 0.00030(ACFM)(hr)
Low Efficiency	kWh/yr = 0.00020(ACFM)(hr)

c) Fuel Costs

Only the fuel costs associated with the operation of afterburners are considered in this group. The cost contributions of water usage, etc., towards the operation of other control devices are judged as minor and are not considered.

The fuel requirement relationships for the five types of afterburners are computed as follows:

BASIS: Inlet temperature of effluent gas = 300°F

Available heat from natural gas

with no excess air at 1400°F = 939 Btu/SCF

950°F = 962 Btu/SCF

Enthalpy of air at 300°F = 4.42 Btu/SCF

(Fan located before afterburner)

	Afterburner type	Exit Temperature F	Btu/SCF	ΔH	SCF Natural Gas per ACFM-hr
019	Catalytic	950°F	16.92	12.50	0.53
020	Catalytic + Heat Exchanger	650°F	11.00	6.58	0.28
021	Direct Flame	1400°F	26.13	21.71	0.95
022	Direct Flame + Heat Exchanger	1000°F	17.92	13.50	0.59
023	Direct Flame + Regenerative	450°F	7.23	2.81	0.12

d) Operating Labor

Operating labor for particulate-control devices is not a major cost contribution.

	<100,000 ACFM	>100,000 ACFM
Scrubbers	6 hr/day	12 hr/day
Settlers / Cyclones	No labor loading	
ESP's	2 hr/day	4 hr/day
Fabric Filters	6 hr/shift	12 hr/day
Mist Eliminators	No labor loading	
Afterburners	No labor loading	

e) Maintenance

Maintenance costs are usually related to the complexity of the installation and not primarily to throughput. Relating maintenance costs to capital investment is an effective approach and appears compatible with the objectives of the Implementation Planning Program. The following relationships are defined based on maintenance factors commonly used in estimating practice:

Scrubbers	0.08 C.I.
Settlers	0.01 C.I.
Cyciones	0.02 C.I.
Electrostatic Precipitators	
High Efficiency	0.04 C.I.
Standard	0.02 C.I.
Fabric Filters	
High Temperature	0.10 C.I.
Low Temperature	0.08 C.I.
Mist Eliminators	0.02 C.I.
Afterburners	0.04 C.I.

f) Disposal Costs

Disposal of solid particulate material may be associated with the following control devices: scrubbers, settlers, cyclones, electrostatic precipitators, fabric filters.

In all cases except scrubbers, certain industries may return the captured particulates to the process and no disposal costs are incurred. However, for the purposes of this program it is assumed that disposal costs will always be incurred. They are calculated from the reported emission rate for particulates in tons/day, the efficiency of the control device (or adjusted efficiency if tandem devices used) and the number of operating days.

Annual Disposal Cost = (E) (η)(Days)($/ton disposal)

where (E) = Uncontrolled particulate emissions in tons/day

(η) = Efficiency of removal of control device

(Days) = Annual days of operation

Representative Disposal Costs are

Scrubbers $3/ton

Cyclones/ESP's/Fabric Filters $2/ton

g) Cost of Taxes and Insurance

Taxes and insurance are usually allowed for as a percentage of the total capital investment. An annual allowance of 2 1/2 percent is commonly used.

6.1.3 Annualized Capital Costs

To evaluate and compare the economics of alternative particulate or SO_2 control equipment or processes, it is necessary to relate for each system, both the annual operating and maintenance costs and the initial capital investment. There are a number of methods whereby the initial capital investment may be converted to an annual value related to the expected life of that particular piece of equipment or system. The simplest approach is to divide the initial capital investment by the expected life of the equipment or investment. This figure can then be interpreted as that part of the initial investment which is "consumed" or "depreciated" each year during the useful lifetime of the equipment. Other depreciation methods such as the sum-of-years digits and declining-balance, accelerate the rate of depreciation in the early life of the asset. All these methods, however, fail to take into consideration the time value of money by neglecting interest. Money not invested in a capital venture could be drawing interest at current bank or security rates. Thus, the evaluation of a capital investment project should consider the effect of interest, and the annual "depreciated" value of this capital investment over its useful life should include the potential interest contributions. This concept of the time value, or present worth of money is inherent in such profitability study techniques as present-worth, interest-rate-of-return, or discounted cash flow. A variation of these criteria is known as the Capitalized Cost Method which involves the use

of an amortization factor ("Capital Recovery Factor") to reduce the capital investment figure to a uniform series of annual values over the life of the investment.

The Capital Recovery Factor (C.R.F.) is expressed as follows:

$$C.R.F. = \frac{i(1 + i)^N}{(1 + i)^N - 1}$$

where,

i = the interest rate $0<i<1$,

N = rated life of the equipment or process.

Thus, if a piece of control equipment has a rated life of 15 years and the interest rate is 10 percent, the Capital Recovery Factor is 0.1315 (or 13.15 percent).

The annual capital charge is then computed as the product of the total capital investment and the C.R.F. value.

It is apparent that the Capital Recovery Factor is the reciprocal of the Present Worth Factor which is defined for a uniform annual series as

$$\frac{(1 + i)^N - 1}{i(1 + i)^N} \quad \text{or} \quad \sum_{t=1}^{N} \left(\frac{1}{1 + i}\right)^t.$$

The total annualized cost of pollution control equipment is thus the sum of the annualized capital charge, all variable operating costs, and the annual maintenance, insurance, and taxes charges. This may be expressed as

$$AC = CRF(I) + (V' + M + T)$$

where,

AC = total annual cost

CRF = capital recovery factor

I = total capital investment

V' = annual variable operating costs

M = maintenance cost (commonly expressed as fraction of total capital investment

T = taxes and insurance (commonly 2 1/2% TCI)

However, present income tax provisions covering the installation of pollution control equipment exercise a significant influence on the final annual cost of such equipment to a corporation. When the income tax rate (expressed as θ) is introduced into the above relationship, total annual costs become:

$$AC = CRF\ (I) + (V' + M + T)(1 - \theta) - \begin{pmatrix} \text{Depreciation} \\ \text{allowance} \\ \text{for (1st) year} \end{pmatrix} \theta$$

The depreciation allowance for any given year depends on the particular depreciation method adopted (e.g., Straight Line) which provides a uniform value over the life of the equipment, or an accelerated method which provides faster write-off over the early life of the equipment. Under normal circumstances, the accelerated approach is favored and the "Sum-of-the-Year's Digits" depreciation method would be used. With this method an-

nual depreciation for any year k, would be defined by the expression:

$$D = \frac{2}{N}\left[\frac{N + 1 - k}{N + 1}\right] I$$

where N = rated life of equipment

D = annual depreciation

If pollution control alternatives are being evaluated on the basis of the annual costs for the first year of operation; the general relationship can be expressed as:

$$AC = CRF\ (I) + (V' + M + T)(1 - \theta) - \frac{2I}{N}\left(\frac{N}{N + 1}\right)\theta$$

for Sum-of-the-Year's Digits depreciation.

6.2 CAPITAL COST EQUATIONS - PARTICULATE CONTROL SYSTEMS

Capital cost of particulate control devices covers the cost of the total system, i.e., equipment, installation, auxiliary materials such as pumps, fans, piping, etc. together with indirect and engineering costs

where,

$x = 10^3$ ACFM

$y = 10^3$ dollars

001, 002, 003 - Wet Scrubbers

1 -	High Cost	$y_1 = 83.8 + 3.8\ x$
2 -	Intermediate Cost	$y_2 = 18.8 + 1.6\ x$
3 -	Low Cost ($\leq$100,000 ACFM)	$y_3 = 7.1 + 1.6\ x$

004, 005, 006 - Settlers

1 -	Cost	$y_1 = -0.34 + 0.40\ x$

007, 008, 009 - Cyclones

1 - High Cost $y_1 = 5.0 + 0.7 x$

2 - Low Cost $y_2 = 2.5 + 0.4 x$

010, 011, 012 - Electrostatic Precipitators

1 - High Cost (High Efficiency) $y_1 = 170 + 3.25 x$

2 - Intermediate Cost (Medium Efficiency) $y_2 = 117 + 2.08 x$

3 - Low Cost (Low Efficiency) $y_3 = 89 + 1.01 x$

014, 015 - Mist Eliminators

1 - High Cost (high velocity) $y_1 = 11.1 + 0.6 x$

2 - Low Cost (low velocity) $y_2 = 5.0 + 0.3 x$

016, 017, 018 - Fabric Filters

1 - High Temperature (> 200 F) $y_1 = -1.0 + 3.5 x$ ($\geq$ 3000 ACFM)

2 - Low Temperature $y_2 = 2.4 + 1.8 x$

019 - Afterburner - Catalytic

1 - Cost $y_1 = 31.3 + 1.1 x$

020 - Afterburner - Catalytic with Heat Exchanger

1 - Cost $y_2 = 51.0 + 2.4 x$

021 - Afterburner - Direct Flame

1 - Cost $y_1 = 25.6 + 0.9 x$

22 - Afterburner - Direct Flame with Heat Exchanger

1 - Cost $y_1 = 24.8 + 1.9 x$

55 - Afterburner - Direct Flame - Regenerative

1 - Cost $y_1 = 55.5 + 4.3 x$

NOTE: The log-log cost curves for the particulate control devices provided in Appendix I have been approximated by the linear equation $y = a+bx$. This format maintains accuracy within the capability of the methodology but offers advantages in implementation.

6.3 ANNUAL OPERATING COST EQUATIONS - PARTICULATE CONTROL SYSTEMS

Scrubbers (001, 002, 003)

$$\text{ANNUAL OPERATING COST (AOC)} = (\text{ACFM}')(\text{Hrs})(\$/\text{kWh})\left[(0.1955 \times 10^{-3})(P) + K\right] + (E)(\eta)(\text{Days})(\$3/\text{ton}) + 0.08(\text{C.I.}) + (L)(\text{Days})(\$/\text{hr}) + 0.025\,(\text{C.L})$$

where

ACFM' = Corrected gas flow rate

$$= \left(\frac{\text{ACFM}}{460 + T}\right)\left[552.4 + 0.289T\right]$$

T = Temperature of source gas °F

P = Pressure drop across scrubber ("H_2O)

K = Constant related to efficiency of scrubber

E = Particulate emission tons/day

η = Efficiency of control device

L = Operating hours factor

C.I. = Capital investment

$$\text{Total Annual Cost} = \left[\frac{i(1 + i)^N}{(1 + i)^N - 1}\right](\text{C.I.}) + (\text{AOC})(1 - \theta) - \left[\frac{2(\text{C.I.})}{N}\,\frac{N}{N + 1}\right]\theta$$

USER INPUTS (See Section 6.4.)

(ACFM)	=	Effluent gas flow rate to scrubber
(Hrs)	=	Annual hours of operation
*($/kWh)	=	Electric power
(P)	=	Pressure drop("H_2O)- Dependent on level of scrubber efficiency selected (Hi = 40"; Med. = 20"; Low = 5")
(K)	=	Constant. Dependent on level of scrubber efficiency selected (Hi = 0.00130; Med. = 0.00052; Lo = 0.00022)
(E)	=	Particulate emission rate(tons/day)
(Days)	=	Annual days of operation
(η)	=	Efficiency
($/hr)	=	Operating labor rate
(L)	=	Operating labor (hours/day)< 100,000 ACFM = 6 > 100,000 ACFM =12

*See table 9 for mid-1974 costs.

Settlers (No annual operating costs assigned)

Centrifugal collector (08, 09)

$$\text{Annual Operating Cost (AOC)} = (0.1955 \times 10^{-3})(\text{ACFM})(P)(\text{Hrs})(\$/\text{kWh}) + (E)(\eta)(\text{Days})(\$2/\text{ton}) + 0.02(\text{C.I.}) + 0.25\ (\text{C.1})$$

USER INPUTS

(ACFM)	=	Effluent gas flow rate to cyclone
(Hrs)	=	Annual hours of operation
*($/kWh)	=	Electric power
(P)	=	Pressure drop ("H_2O) - Dependent on level of cyclone efficiency selected(5"; 3")
(E)	=	Particulate emission rate(tons/day)
(η)	=	Efficiency
Total Annual Cost	=	(See Section 6.4)

Electrostatic Precipitators (010, 011, 012)

$$\text{Annual Operating Cost (AOC)} = (\text{ACFM})\ (\$/\text{kWh})(\text{Hrs})\left[(0.1955 \times 10^{-3})(0.5) + K\right] + (E)(\eta)(\text{Days})\ (\$2/\text{ton}) + (M)(\text{C.1}) + (L)(\text{days})(\$/\text{lw}) + (0.025)(\text{C.1})$$

USER INPUTS

(ACFM)	=	Effluent gas flow rate to ESP
(Hrs)	=	Annual hours of operation
*($/kWh)	=	Electric power
($/hr)	=	Labor rate
(K)	=	Constant. Dependent on level of ESP efficiency selected (Hi. = 0.0004; Med. = 0.0003; Lo = 0.0002)
(E)	=	Particulate emission rate (tons/day)
(η)	=	Efficiency
(M)	=	Maintenance constant {0.04 high efficiency; 0.02 standard}
(Days)	=	Annual days of operation
(L)	=	Operating labor factor(hours/day) < 100,000 ACFM = 2; > 100,000 ACFM = 4
Total Annual Cost	=	(See Section 6.4)

*See table 9 for mid-1974 costs.

Fabric Filters (016, 017)

$$\text{Annual Operating Cost (AOC)} = (\text{ACFM})\,(\$/\text{kWh})(\text{Hrs})\left[(0.1955 \times 10^{-3})(5)\right]\left[0.9775 \times 10^{-3}\right] + (E)(\eta)(\text{Days})(\$2/\text{ton}) + (L)(\text{Days})(\$/\text{hr}) + (M)(\text{C.I.}) + (0.025)(\text{C.1})$$

USER INPUTS

(ACFM)	=	Effluent gas flow rate to filter
(Hrs)	=	Annual hours of operation
*($/kWh)	=	Electric power
($/hr)	=	Labor rate
(E)	=	Particulate emission rate (tons/day)
(η)	=	Efficiency
(Days)	=	Annual days of operation
(M)	=	Maintenance Constant {0.10 high temperature >200°F; 0.08 low temperature
(L)	=	Operating labor (hours/day <100,000 ACFM = 6; >100,000 ACFM = 12
Total Annual Cost	=	(See Section 6.4)

Mist Eliminator (014, 015)

$$\text{Annual Operating Cost (AOC)} = (0.1955 \times 10^{-3})(\text{ACFM})(P)(\text{Hrs})(\$/\text{kWh}) + 0.02\,(\text{C.I.}) + (0.025)(\text{C.1})$$

USER INPUTS

(ACFM)	=	Effluent gas flow rate to mist eliminator
(Hrs)	=	Annual hours of operation
*($/kWh)	=	Electric power
(P)	=	Pressure drop across eliminator - 10" high efficiency; 5" low efficiency
Total Annual Cost	=	(See Section 6.4)

Afterburners (019, 020, 021, 022, 023)

$$\text{Annual Operating Cost (AOC)} = (\text{ACFM})(\text{Hrs})\left[(0.1955 \times 10^{-3})(P)(\$/\text{kWh}) + (F)(\$/\text{MCF})\right] + 0.04(\text{C.I.}) + (0.025(\text{C.1})$$

Total Annual Cost = (See Section 6.4)

USER INPUTS

(ACFM)	=	Effluent gas flow to afterburner
(Hrs)	=	Annual hours of operation
*($/kWh)	=	Electric power
*($/MCF)	=	Natural gas
(F)	=	Fuel constant dependent on type afterburner 019 = 0.53, 020 = 0.28, 021 = 0.95, 022 = 0.59, 023 = 0.12

*See table 9 for mid-1974 costs.

Table 9. Utility unit costs for particulate control systems as of mid-1974

Electric Power	$0.015/kWh
Natural Gas	$1.25/M CF

6.4 TOTAL ANNUAL COSTS EQUATION - PARTICULATE CONTROL SYSTEMS

The total annual cost (TAC) for all systems if the effect of taxation is ignored, is

$$TAC = \left[\frac{i(1+i)^N}{(1+i)^N - 1} \right] (C.1) + (\text{Annual Operating Cost})$$

When the effect of taxation rate is included, the sum-of-the-year's digit's method of accelerated depreciation is used, the annualized capital cost for the first year reduces

$$TAC = \left[\frac{i(1+i)^N}{(1+i)^N - 1} \right] (C.1) + (\text{Annual operating cost})(1-\theta) - \left[\frac{2(C.1)}{N} \left(\frac{N}{N+1} \right) \right] \theta$$

where i = interest rate

N = rated life of control device

θ = the taxation rate, where $0<\theta<1$

$C.1$ = capital investment

Values of N for the listed particulate control devices:

Scrubbers	15 years
Settlers	20 years
Centrifugal collector	15 years

Electrostatic Precipitators	15 years
Fabric Filters	15 years
Gas Scrubbers	15 years
Mist Eliminators	15 years
Afterburners	15 years

The Internal Revenue Department Publication 534(10-72), "Tax Information on Depreciation," provides write-off periods for industries as a whole. Twelve to fifteen years appears to be the usual period for such industries as pulp, iron and steel mills, and swelters which utilize particulate recovery equipment.

7.0 SULFUR DIOXIDE CONTROL SYSTEM COSTS

7.1 DISCUSSION

The list of processes and systems which, in theory at least, offer promise as practical SO_2 control methods is both long and varied. However, few processes have been demonstrated under full scale commercial plant conditions although a number today are currently undergoing small scale testing and evaluation.

This situation introduces considerable uncertainty regarding the final costs and operating performance of most SO_2 control processes. Costs reported in the literature are frequently sketchy and commonly do not define the approach taken in regard to indirect costs, engineering costs, contingencies, contractors fees, etc.

For this reason, only a limited number of SO_2 control processes has been selected for-cost-equation development for the Implementation Planning Program. It is believed that these selected processes are representative of the types of SO_2 control processes available and that the cost equations developed will be equally representative. The cost functions include an allowance for retrofitting to an existing facility.

Process input parameters have been limited to the effluent gas flow rate (ACFM), the daily SO_2 emission rate in tons per day (E), and the temperature of the effluent gas ($^{\circ}F$) to facilitate direct input from the NEDS files. Table 10 provides SO_2 concentration limitations in the application of specific SO_2 control systems.

The specific SO_2 recovery limits which have been assigned to each selected process represent typical expected values but obviously in real-life application this value may vary considerably.

Table 10. SO_2 concentration limitations in the application of SO_2 control systems

	Minimum % SO_2 in Effluent Gas
Single Absorption Sulfuric Acid Plants	3.5%
Double Absorption Sulfuric Acid Plants	4.0%
Sulfur Plants	10.0%
Dimethylaniline Scrubbing	1.5%
Limestone Scrubbing Wellman-Lord Process Citrate Process Double Alkali Molecular Sieves	No Minimum Limit

In developing equations for annual operating costs, a number of simplifications have been adopted and these are listed below.

1) Utilities and raw materials have been determined on the basis of fixed relationships to the process input parameters for each SO_2 control process which are constant over the entire range of application. Representative costs for utilities and raw materials as of mid-1974 are provided in appendix II.

2) Operating hourly labor has been specified and fixed for each process with coverage for the full year (365 days) irrespective of the actual days of operation. An additional 20 percent has been included for supervision and benefits. No allowance for plant overhead has been provided since these plants do not contribute normally to plant output. The hourly rate is a user input variable.

3) Maintenance charges have been taken as a specified percentage of the process capital investment.

4) Taxes and insurance have been taken at 2 1/2% of the total capital investment.

5) Conditions for marketing the output from those SO_2 control processes which produce sulfuric acid, elemental sulfur or SO_2 are uncertain. Income from disposal may range from going market prices through negative values. Credit or debit values per unit of production have been designated as user inputs.

The equation for annual capital charges has been developed using the "Capital Recovery Factor" technique and includes the impact of the income tax rate on these capital charges when depreciation is based on the Sum-of-the-Year's Digits approach. Section 6.1.3 provides a brief discussion on this treatment.

The total annual cost of any control system is obtained by summing the annual operating costs and the annual capital charges.

7.1.1 Selection of the SO_2 Control System

Although entries have been made in the Device Applicability Matrix for SO_2 control systems compatible with specific industries and processes, the variability of SO_2 concentrations possible even within the same industry and process suggest that an alternative approach to the matching of SO_2 control systems may be advantageous.

Table 10 provides the SO_2 minimum concentration limits for the SO_2 control systems costed in the program and these values could provide a decision-making capability in the selection process.

An additional advantage could be obtained by differentiating between weak or low strength SO_2 effluent streams on the basis of whether they are tail gas streams from primary SO_2 control systems or direct effluent streams from the process itself. With tail gas streams, e.g., from single absorber sulfuric acid plants, sulfur plants, or Claus units, only a scrubbing-concentrating process is required with recirculation of the concentrated SO_2 gas back to the primary SO_2 control system. Molecular sieves, dimethylaniline scrubbing, or the Wellman-Lord process without the sulfur plant provide this option.

7.1.2 Wet Gas Cleaning[23]

Sulfur oxide control processes which produce a final product of elemental sulfur, sulfuric acid, and liquid or gaseous SO_2 require a feed gas which is essentially free of particulate matter and excess water vapor. It has been assumed that prior particulate removal devices will reduce particulate loading in an effluent stream down to 0.1 - 0.2 gr/SCF and that

additional gas cleaning and conditioning is necessary prior to sulfur recovery processes applied as primary SO_2 control systems.

The degree of additional treatment required will be related to the particular source of the effluent gases. Smelter gases will require the most extensive treatment involving water scrubbing from temperatures of the order of 500 - 600 °F, electrostatic precipitation of acid mist, and air stripping of dissolved SO_2 together with neutralization, thickener, and recirculation facilities to handle the resulting slurry and solid material. However, even power plants' effluent-gas streams directed to sulfur recovery processes may require additional wet-gas cleaning to remove such contaminants as chlorine, etc.

The development of a cost equation for wet-gas cleaning thus poses some difficulties. Where gas cleaning is universally required with a sulfur recovery process, the cost has been incorporated with the cost equation for that process, e.g., sulfuric acid plants. Where the sulfur recovery process may be applied either as a primary SO_2 control or as a tail gas SO_2 clean-up or secondary process, gas cleaning and conditioning will not be required in the latter situation, and a separate cost function for gas cleaning is necessary.

The approach taken has been to develop a cost equation for a system comprised of

- humidifying/scrubber section,
- demister,
- thickener.

Such a system may not fully satisfy the gas treatment requirements of a smelter but it will provide a reasonable overall approach.

The cost equation for gas cleaning has been developed on the basis of SCFM rather than ACFM to better accommodate the variability in the input-gas temperature ranges. Since the source data provides only ACFM, the cost equation includes a conversion of ACFM to SCFM. Operating costs are also based on SCFM, and an overall cost function provided for total annualized costs. The function should be activated and the annualized costs added to the annualized costs for the primary SO_2 control system when the following conditions are applicable unless otherwise qualified by the specific cost equation:

1) Effluent gas temperature > 130°F, and/or

2) Particulate loading of effluent gas stream > 0.01 gr/SCF.

Gas conditioning will change the actual gas volume to the primary SO_2 control process and it is necessary to determine this new gas volume for input to the primary control process cost equation. The derivation of an expression for this new volume based on the initial temperature and ACFM of the gas stream is provided below.

BASIS:
1. Effluent gas cooled and conditioned to 130°F;
2. Specific heat of effluent gas taken as 0.24 Btu/lb/°F;
3. Molecular weight effluent gas taken as 30.4;
4. Latent heat of vaporization of water at 60°F = 1,060 Btu/lb;
5. Temperature in °F.

If ACFM is the unconditioned effluent gas rate, then the heat load to be removed from T°F to 130°F

$$= \frac{ACFM}{359} \left(\frac{590}{460 + T} \right) 30.4 \times 0.24(T - 130),$$

$$= \frac{11.99(ACFM)}{(460 + T)} (T - 130) \text{ Btu/min.}$$

$$\text{water required} = \frac{11.99(ACFM)(T - 130)}{(460 + T)\ 1060} \text{ lbs/min}$$

$$\text{Volume of water at } 130°F = \frac{359}{18}\left(\frac{590}{460}\right)\left[\frac{11.99(ACFM)(T - 130)}{(460 + T)\ 1060}\right]$$

$$= \frac{0.289(ACFM)(T - 130)}{(460 + T)}.$$

$$\text{Volume of effluent gas at } 130°F = ACFM \times \frac{590}{460 + T}.$$

$$\text{Total new volume}(ACFM') \left(\frac{ACFM}{460 + T}\right)\left[552.4 + 0.289T\right]$$

where $ACFM'$ = Effluent gas rate ACFM after conditioning and cooling to 130°F.

7.1.3 Sulfuric Acid Plants

The references for this section provide considerable information on acid plants but it is difficult to compare the provided cost data. The Chemico work is directed towards the H_2SO_4 industry itself whereas the IPP approach considers the application of sulfuric acid plants as SO_x emission control devices. An important additional cost factor must thus be considered in any cost determination and that involves the gas cleaning and conditioning equipment which must be provided prior to any H_2SO_4 plant operating as an SO_x control device.

Whether the acid produced is marketed or disposed of via neutralization, some storage facilities must be provided and legitimately constitute part of the cost of the acid plant as a control device.

Almost all H_2SO_4 plants installed in the United States are single-absorption units and as such are capable of attaining an SO_2 recovery efficiency of approximately 97 percent. Without additional tail gas clean-up facilities, such plants cannot meet today's emission standards. However, such plants may be satisfactory in those situations where the tail gas may be recirculated back to an on-site scrubbing system. In other circumstances, the plant may be upgraded by the addition of a second absorber section although additional tail gas clean-up treatment may still be required to meet proposed standards.

Cost equations have been developed for the following cases

1) Single absorption plant,
2) Double absorption plant,
3) Add-on second absorption section.

Since smelter operations commonly use acid plants today as SO_x control devices, metallurgical acid plants are sold as turnkey units and include wet cleaning equipment such as scrubbers, mist eliminators, etc. The cost equations therefore include gas cleaning and conditioning. Acid storage is also included and allowance is made for site clearance and utility hook-up and retrofitting to an existing emission producing plant.

In developing the cost equations, the effect of SO_2 concentration in the gas stream has been taken into effect as well as the SO_2 emission rate itself. J.M. Connor in Chemical Engineering Progress, Vol.64, No. 1, Nov. 1968, indicates that percent SO_2 has a significant influence on costs.

Cost of add-on absorption is related to the original plant capacity but is expressed in terms of H_2SO_4 produced and SO_2 concentration in the inlet gas.

DETERMINATION OF DECIMAL FRACTION OF SO_2 IN EFFLUENT GAS

Provided Data:

E = SO_2 emission rate TPD

ACFM = Flow rate of effluent gas

Volume of SO_2 at 32°F and 14.7 lb/in^2

$$= \frac{(E)(2000)(359)}{(24)(60))64)} \text{ ft}^3/\text{min.}$$

Since source temperature data is reported in °F, then:

$$\text{Volume } SO_2 \text{ at } T\,^\circ\text{F} = \frac{(E)(2000)(359)}{(24)(60)(64)} \times \frac{(460 + T)}{492} \text{ ACFM.}$$

Decimal fraction SO_2 in effluent gas

$$= (7.791)\,\frac{(460 + T)}{492}\,\frac{E}{ACFM}$$

$$= (7.284 + 0.0158\ T)\,\frac{E}{ACFM}.$$

7.1.4 Sulfur Plants[28]

The direct application of sulfur plants to SO_2 carrying streams is probably limited to situations where the SO_2 concentration is greater than 10 percent and the oxygen content is less than 1-3 percent. Although the process may be applied as a primary SO_2 control process, e.g., for certain non-ferrous smelter gas streams, it will usually be incorporated with some primary SO_2 concentrating process such as citrate scrubbing and sodium sulfite scrubbing. In this program, the cost of elemental sulfur plants providing a secondary function has been incorporated with the overall cost function for the primary SO_2 control system.

7.1.5 Molecular Sieves[29]

Molecular sieves are tail gas clean-up systems. They have been applied commercially to sulfuric acid plants but are applicable to any SO_2-containing tail gas. Switching sequences between absorption and regeneration are automatic. No additional labor is required to operate the system.

7.1.6 Dimethylaniline Scrubbing[30-32]

Dimethylaniline (DMA) scrubbing is an SO_2 concentrating process capable of yielding 100 percent liquid or gaseous SO_2 product. Although it can be designed to handle weak SO_2 containing streams (0.5% SO_2), it is generally applied to streams containing 1.5 percent SO_2 or more.

Since the process is applied to primary SO_2 sources, gas scrubbing and conditioning is necessary prior to the DMA process itself, and the cost function developed includes this cost. Costs of both the gas conditioning section and the DMA scrubbing system are based on gas flow (ACFM) and the derived cost equation incorporates the necessary calculation of the new gas flow from the conditioning section as input to determine the DMA scrubbing cost.

7.1.7 SO_2 Absorbent Systems

There are a large number of SO_2 aqueous absorbent systems which might be viewed as potential commercially applicable SO_2 control systems. Very few, however, have progressed beyond the small scale demonstration size and of these, the majority have been applied to utility power generation facilities. The cost picture accordingly, is rather unstable with estimated costs for particular systems escalating dramatically as knowledge is broadened and designs modified accordingly.

Four SO_2 aqueous absorbent systems have been chosen as representatives of present scrubbing technology. These are:

1) Limestone Scrubbing - non-regenerable throwaway system;
2) Wellman-Lord (Sodium Sulfite Scrubbing) - regenerable with SO_2 or sulfur recovery;
3) Citrate Process - regenerable with sulfur recovery;
4) Double-Alkali Process - regenerable scrubbing medium, throwaway solids.

The processes may be applied as primary SO_2 control systems or as secondary or tail gas clean-up systems. The Wellman-Lord process provides a further option of recirculating the recovered SO_2 back to the primary control system or of producing elemental sulfur.

Table 11 provides a listing and grouping of sulfur dioxide desulfurization processes which today are being evaluated in either commercial installations or small scale demonstration units. The individual cost equations developed for the above processes are believed to be reasonably representative of the costs of those processes within their own group.

It should be noted that table 2 provides among the listing of SO_2 control systems, two methods which are not included in table 11. These methods -- namely, dry limestone injection and alkalized alumina--do not appear today to offer potential as commercial SO_2 control methods although they have been retained in the record to avoid possible conflict with the NEDS files.

Table 11. SO_2 desulfurization processes (Presently under evaluation)

(A)	NON-REGENERABLE THROWAWAY SYSTEMS
	*Limestone Scrubbing
	Lime Scrubbing
(B)	REGENERABLE WITH SO_2 OR SULFUR RECOVERY SYSTEMS
Group I:	*Wellman-Lord Process
	Magnesia (MgO) Scrubbing
	Ammonia Scrubbing
	Catalytic Oxidation (Cat-Ox Process)
Group II:	*Citric Acid
	*Double-Alkali Process (Throwaway Solids)
	Sodium Phosphate Scrubbing (Stauffer's Powerclaus Process)

*Processes selected for costing and inclusion in the program.

7.2 CAPITAL, OPERATING, AND ANNUALIZED CAPITAL COST EQUATIONS

(043, 044, 033) SULFURIC ACID PLANTS

Capital Cost Equations (Includes gas cleaning and conditioning, acid storage and retrofitting)

043 SINGLE ABSORPTION (RECOVERY 97.5%)

$$\text{CAPITAL COST (C.I.)} = 112{,}000 \left(\frac{0.08}{\%SO_2}\right)^{0.60} (E)^{0.68}$$

044 DOUBLE ABSORPTION (RECOVERY 99.5%)

$$\text{CAPITAL COST (C.I.)} = 128{,}000 \left(\frac{0.08}{\%SO_2}\right)^{0.60} (E)^{0.68}$$

033 ADD-ON DOUBLE ABSORPTION

$$\text{CAPITAL COST (C.I.)} = 29{,}500 \left(H_2SO_4\right)^{0.62}$$

where,

$\%\ SO_2$ = Decimal fraction SO_2 in effluent gas

$$= (7.284 + 0.0158T)\ \frac{E}{ACFM}$$

T = Effluent gas temperature °F)

E = SO_2 emission rate in tons/day

H_2SO_4 = Sulfuric acid production from single absorption plant as 100% TPD

ACFM = Effluent gas flow rate

CAPITAL, OPERATING AND ANNUALIZED CAPITAL COST EQUATIONS

043 SINGLE ABSORPTION

ANNUAL OPERATING COST

$$AOC = (E)(Days)\left[95.55(\$/kWh) + 1.64(\$/M\ gal)\right] + 21{,}024(\$/hr) + 0.06(C.I.) + 0.025(C.I.)$$

TOTAL ANNUAL CHARGES

$$TAC = \left[\frac{i(1+i)^N}{(1+i)^N - 1}\right](C.I.) + (AOC)(1-\theta) - \left[\frac{2(C.I.)}{N}\left(\frac{N}{N+1}\right)\right]\theta$$

where,

θ = taxation rate $0 < \theta < 1$
i = interest rate
N = life of equipment

ANNUAL H_2SO_4(100%) PRODUCTION = 1.49(Days)(E)

044 DOUBLE ABSORPTION

ANNUAL OPERATING COST

$$AOC = (E)(Days)\left[118.84(\$/kWh) + 1.68(\$/M\ gal)\right] + 21{,}024(\$/hr) + 0.06(C.I.) + 0.025\ (C.I.)$$

TOTAL ANNUAL CHARGES

$$TAC = \left[\frac{i(1+i)^N}{(1+i)^N - 1}\right](C.I.) + (AOC)(1-\theta) - \left[\frac{2(C.I.)}{N}\left(\frac{N}{N+1}\right)\right]\theta$$

where,

θ = taxation rate $0 < \theta < 1$
i = interest rate
N = life of equipment

ANNUAL H_2SO_4(100%) PRODUCTION = 1.53(Days)(E)

CAPITAL, OPERATING AND ANNUALIZED CAPITAL COST EQUATIONS

033 ADD-ON DOUBLE ABSORPTION

ANNUAL OPERATING COST

$$AOC = 14.29(Days)(H_2SO_4)(\$/KWH) + 0.06(C.I.) + 0.025(C.I.)$$

TOTAL ANNUAL CHARGES

$$TAC = \left[\frac{i(1+i)^N}{(1+i)^N - 1}\right](C.I.) + (AOC)(1-\theta) - \left[\frac{2(C.I.)}{N}\left(\frac{N}{N+1}\right)\right]\theta$$

where,

θ = taxation rate $0 < \theta < 1$
i = interest rate
N = life of equipment

ADDITIONAL ANNUAL H_2SO_4(100%) PRODUCTION = $1.02(H_2SO_4)(Days)$

where,

E = SO_2 emission rate tons/day
Days= Annual days of operation
C.I.= Capital investment
H_2SO_4= Daily production H_2SO_4(100%)

OPERATING DATA BASIS

	Single Absorption	Double Absorption
Power:	64 kWh/ton H_2SO_4	78 kWh/ton H_2SO_4
Process and Cooling Water:	1.1 M gal/ton H_2SO_4	1.1 M gal/ton H_2SO_4
Labor:	Fixed at 2 men/shift (With 20% allowance for fringes and benefits)	
Maintenance:	0.06 C.I.	
Capital Charges:	15 year life Taxes, insurance, etc. 2.5%(C.I.)	

USER INPUTS

(E) = SO_2 emission rate-tons/day
(Days) = Annual days of operation
*($/kWh) = Electric power
*$/M gal) = Process water
*($/short ton) 100% H_2SO_4
($/hr) = Labor
(i) = Interest rate

*See appendix II for mid-1974 costs.

CAPITAL, OPERATING AND ANNUALIZED CAPITAL COST EQUATIONS

045 SULFUR PLANT (RECOVERY 90%)

NOTE: (Does not include gas cleaning and conditioning)

$$\text{CAPITAL COST (C.I.)} = 105{,}400\left(\frac{1}{\%SO_2}\right)^{0.43}(E)^{0.58}$$

where,

E = SO_2 emission rate in tons/day

$\%SO_2$ = Decimal

$$= \frac{E}{ACFM}(7.284 + 0.0158T)$$

ACFM = Effluent gas flow rate

$$\text{ANNUAL OPERATING COST} \quad AOC = (E)(Days)\left[18\left(\frac{1}{SO_2}\right)^{0.80}(\$/kWh) + 6.03\left(\frac{1}{SO_2}\right)^{0.17}(\$/M\ CF\ methane) + 1.71(\$/lb)_{catalyst} + 0.81\left(\frac{1}{SO_2}\right)^{0.40}(\$/M\ gal)_{water}\right] + 21{,}024(\$/hr) + 0.06(C.I.) + 0.025(C.I.)$$

$$\text{TOTAL ANNUAL CHARGES} \quad TAC = \left[\frac{i(1+i)^N}{(1+i)^N - 1}\right](C.I.) + (AOC)(1-\theta) - \left[\frac{2(C.I.)}{N}\left(\frac{N}{N+1}\right)\right]\theta$$

where, θ = taxation rate $0 < \theta < 1$

i = interest rate

N = life of equipment

ANNUAL SULFUR PRODUCTION CREDIT = $0.45(E)(Days)(\$/short\ ton\ sulfur)$

OPERATING DATA INPUT

Power:	40 kWh /ton sulfur
Methane:	13.4 M CF/ton sulfur
Cooling Water:	1.8 M gal/ton sulfur
Catalyst:	3.8 lb/ton sulfur
Labor:	Fixed at 2 men/shift (includes 20% allowance for fringes and benefits)
Maintenance:	0.06 C.I.
Capital Charges:	15 year life Taxes, insurance, etc. 2.5% C.I.

USER INPUTS

(E)	=	SO_2 emission rate TPD
(Days)	=	Annual days of operation
*($/kWh)	=	Electric power
*($/M gal)	=	Cooling water
*($/M CF)	=	Methane
*($/lb)	=	Catalyst
($/hr)	=	Labor
(ACFM)	=	Effluent gas flow rate
(T)	=	Effluent gas temperature °F
(i)	=	Interest rate

*See appendix II for mid-1974 costs.

CAPITAL, OPERATING AND ANNUALIZED CAPITAL COST EQUATIONS

057 MOLECULAR SIEVE (RECOVERY 98%)

(Tail gas clean-up process)

CAPITAL COST (C.I.) = $850(ACFM)^{0.70}$

ANNUAL OPERATING COST AOC = $(Days)\left[0.024(ACFM)^{1.3}(\$/kWh) + 32.6(E)^{0.25}(\$/MM\ Btu)\right] + 0.13(C.I.)$

where,

(ACFM) = effluent gas flow rate
(E) = SO_2 emission rate TPD
C.I. = capital investment

TOTAL ANNUAL CHARGES TAC = $\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right](C.I.) + (AOC)(1-\theta) - \left[\frac{2(C.I.)}{N}\left(\frac{N}{N+1}\right)\right]\theta$

where,

θ = taxation rate $0 < \theta < 1$
i = interest rate
N = life of equipment

ANNUAL SO_2 PRODUCTION CREDIT (as 100% H_2SO_4) = (1.5)(E)(Days)($/short ton 100% H_2SO_4)

OPERATING DATA INPUT

Power:	0.024 kWh $(ACFM)^{1.3}$
Heat:	6.94 MM Btu/ton SO_2
Sieve Replacement(every 2 years)	0.08(C.I.)
Maintenance:	0.05 C.I.
Labor:	None
Capital Charges:	15 year life Taxes, insurance, etc. 2.5% C.I.

USER INPUTS

(ACFM)	=	Effluent gas flow rate
(Days)	=	Annual days of operation
*($/kWh)	=	Power
*($/MM Btu)	=	Heat
*($/short ton)	=	100% sulfuric acid
(i)	=	Interest rate

* See appendix II for mid-1974 costs.

CAPITAL, OPERATING AND ANNUALIZED CAPITAL COST EQUATIONS

034 WELLMAN-LORD PROCESS (SO_2 RECOVERY 90%)

(Includes particulate scrubbing)

Maximum Sized Unit: 350,000 ACFM

A. Primary SO_2 Control System with Production of Elemental Sulfur

$$\text{CAPITAL COST (C.I.)} = 1800(\text{ACFM})^{0.60} + 250{,}000(\text{E})^{0.65}$$

where,

(ACFM) = effluent gas flow rate
(E) = SO_2 emission rate tons/day

$$\text{ANNUAL OPERATING COST} \quad \text{AOC} = \left(\frac{\text{ACFM}}{1000}\right)(\text{Days})\left[300(\$/\text{kWh}) + 1.5^{*}(\$/\text{MM Btu})\right]$$

$$+ \ (\text{E})(\text{Days})\left[166.3(\$/\text{kWh} + 9.22(\$/\text{M lb steam}) + 0.8(\$/\text{M gal } H_2O)\right.$$

$$+ \ \left.6.37(\$/\text{M CF methane}) + 71.25(\$/\text{lb } Na_2CO_3)\right]$$

$$+ \ 26{,}280\ (\$/\text{hr}) + 0.06\,(\text{C.I.}) + 0.025(\text{C.I.})$$

*Utility applications only.

$$\text{TOTAL ANNUAL CHARGES} \quad \text{TAC} = \left\{\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right](\text{C.I.}) + (\text{AOC})\,(1-\theta) - \left[\frac{2(\text{C.I.})}{N}\left(\frac{N}{N+1}\right)\right]\theta\right.$$

where,

θ = taxation rate $0 < \theta < 1$
i = interest rate
N = life of equipment

ANNUAL ELEMENTAL SULFUR PRODUCTION CREDIT OR DEBIT

$$= 3.2(E)(\text{Days})(\$/\text{ton})$$

B. Tail Gas SO_2 Control System with Recirculation of Gaseous SO_2 to Primary Control System

$$\text{CAPITAL COST (C.I.)} = 1200(\text{ACFM})^{0.60} + 185{,}000(E)^{0.65}$$

where,

(ACFM) = tail gas flow rate
(E) = SO_2 emission rate tons/day

$$\text{ANNUAL OPERATING COST (AOC)} = \left(\frac{\text{ACFM}}{1000}\right)(\text{Days})\left[300(\$/\text{kWh})\right] + (E)(\text{Days})\left[142.5(\$/\text{kWh}) + 9.98(\$/\text{M lb steam}) + 71.25(\$/\text{lb } Na_2CO_3)\right] + 21{,}024\ (\$/\text{hr}) + 0.06(\text{C.I.}) + 0.025\ (\text{C.I.})$$

$$\text{TOTAL ANNUAL CHARGES} \quad TAC = \left[\frac{i(1+i)^N}{(1+i)^N - 1}\right](\text{C.I.}) + (\text{AOC})(1-\theta) - \left[\frac{2(\text{C.I.})}{N}\left(\frac{N}{N+1}\right)\right]\theta$$

where,

θ = taxation rate $0 < \theta < 1$
i = interest rate
N = life of equipment

ANNUAL SO_2 PRODUCTION CREDIT OR DEBIT = 0.90 (E)(Days)($/ton)

OPERATING DATA INPUT

Power: Scrubbing 0.30 kWh/ACFM-day

Sulfur Handling 350 kWh/ton sulfur

Sulfur Handling(as SO_2) 300 kWh/ton sulfur

Steam: 19.4 M lb/ton sulfur

21 M lb/ton sulfur (no elemental sulfur production)

Soda ash(Na_2CO_3): 150 lb/ton sulfur

Cooling Water: 1.7 M gal/ton sulfur } for elemental sulfur

Methane: 13.4 M CF/ton sulfur }

Labor: Fixed at 2½ men/shift(2 men/shift-SO_2 only)
(with 20% allowance for fringe-benefits)

Maintenance: 0.06 C.I.

Capital Charges: 15 year life
Taxes, insurance, etc. 2.5% C.I.

USER INPUTS

(ACFM)	=	Effluent gas flow rate
(E)	=	SO_2 emission rate-tons/day
(Days)	=	Annual days of operation
*($/kWh)	=	Electric power
*($/M lb)	=	Steam
*($/M gal)	=	Cooling water
*($/lb)	=	Soda ash (Na_2CO_3)
*($/M CF)	=	Methane
*($/MM Btu)	=	Reheat (for utility applications)
($/hr)	=	Labor rate
*($/short ton)	=	Credit or debit for elemental sulfur disposal
(i)	=	Interest rate

*See appendix II for mid-1974 costs.

CAPITAL, OPERATING AND ANNUALIZED CAPITAL COST EQUATIONS

042 LIMESTONE SCRUBBING (SO_2 RECOVERY 85%)

(NOTE: Does not require gas conditioning - includes particulate scrubbing)

Maximum Sized System: 350,000 ACFM

$$\text{CAPITAL COST (C.I.)} = 1170\,(\text{ACFM})^{0.65} + 125{,}000(\text{E})^{0.75}$$

where,

(ACFM) = effluent gas flow rate
(E) = SO_2 emission rate tons/day

$$\text{ANNUAL OPERATING COST(AOC)} = \left(\frac{\text{ACFM}}{1000}\right)(\text{Days})\left[300(\$/\text{kWh}) + 1.5^{*}(\$/\text{MM Btu})\right]$$

$$+ (\text{E})(\text{Days})\left[153(\$/\text{kWh}) + 1.9(\$/\text{MM Btu}) + 2.34\ (\$/\text{ton } CaCO_3)\right]$$

$$+ 21{,}024(\$/\text{hr}) + 0.06(\text{C.I.}) + 0.025(\text{C.I.})$$

*Utility applications only.

$$\text{TOTAL ANNUAL CHARGES TAC} = \left[\frac{i(1+i)^N}{(1+i)^N - 1}\right](\text{C.I.}) + (\text{AOC})(1-\theta) - \left[\frac{2(\text{C.I.})}{N}\left(\frac{N}{N+1}\right)\right]\theta$$

where,
θ = taxation rate $0 < \theta < 1$
i = interest rate
N = life of equipment

ANNUAL SLUDGE PRODUCTION = (Days)(6.5 E) tons/day (@50% solids)

NOTE: Capital cost includes disposal pond. Therefore operating costs do not include specific charge for sludge disposal.

OPERATING DATA INPUT

Power:	Scrubbing 0.30 kWh/ACFM-day
	Alkali Handling 360 kWh/ton sulfur
Water:	4.5 M gal/ton sulfur
Reheat:	0.0015 MM Btu/ACFM-day (utility applications only)
Limestone:	5.5 tons/ton sulfur
Labor:	Fixed at 2 men/shift (with 20% allowance for fringes and benefits)
Maintenance:	0.06 C.I.
Capital Charges:	15-year life Taxes, insurance, etc. 2.5% C.I.

USER INPUTS

(ACFM)	=	Effluent gas flow rate
(E)	=	SO_2 emission rate-tons/day
(Days)	=	Annual days of operation
*($/kWh)	=	Electric power
*($/M gal)	=	Raw water
*($/ton)	=	Limestone
*($/MM Btu)	=	Reheat (for utility applications)
($/hr)	=	Labor rate
(i)	=	Interest rate

*See appendix II for mid-1974 costs.

CAPITAL, OPERATING AND ANNUALIZED CAPITAL COST EQUATIONS

056 DIMETHYLANILINE SCRUBBING (98% RECOVERY)

(Includes additional gas cleaning and conditioning prior to DMA Scrubbing System)

$$\text{CAPITAL COST (C.I.)} = 750\ \text{ACFM} \times \left[\frac{520}{460 + T}\right]^{0.68} + 5100\left[\left(\frac{\text{ACFM}}{460 + T}\right)555 + 0.27\ T\right]^{0.7}$$

where,

ACFM = Effluent gas flow rate
T = Temperature (°F) of effluent gas

$$\text{ANNUAL OPERATING COST} \quad \text{AOC} = (\text{Days})\left(\frac{\text{ACFM}}{1000}\right)\left\{\left(\frac{520}{460 + T}\right)\left[245\ (\$/\text{kWh}) + 13(\$/\text{M gal})_{\text{water}}\right.\right.$$
$$+ \left[446(\$/\text{kWh}) + 5.3(\$/\text{M lb})_{\text{steam}} + 37(\$/\text{M gal condensate})\right.$$
$$\left.\left. + 4.6(\$/\text{lb DMA}) + 167(\$/\text{lb } H_2SO_4) + 147(\$/\text{lb } Na_2CO_3)\right]\right\}$$
$$+ 15{,}768(\$/\text{hr}) + 0.06(\text{C.I.}) + 0.025\ (\text{C.I.})$$

$$\text{TOTAL ANNUAL CHARGES} \quad \text{TAC} = \left[\frac{i(1 + i)^N}{(1 + i)^N - 1}\right](\text{C.I.}) + (\text{AOC})\ (1 - \theta) - \left[\frac{2(\text{C.I.})}{N}\left(\frac{N}{N + 1}\right)\right]\theta$$

where,

θ = taxation rate $0 < \theta < 1$
i = interest rate
N = life of equipment

ANNUAL 100% LIQUID OR GASEOUS SO_2 PRODUCTION CREDIT = (E)(Days)(0.98)($/ton)

where,

E = SO_2 emission rate TPD
Days = Annual days of operation

OPERATING DATA INPUT

Conditioning

Power:	245 kWh /M SCFM - day)	Note Basis SCFM
Water:	13 M gal/M SCFM - day	

Scrubbing

Power:	446 kWh/M ACFM-day
Steam:	5.3 lb/M ACFM-day
Condensate:	37 M gal/M ACFM-day
DMA:	4.6 lb/M ACFM-day
H_2SO_4:	167 lb/M ACFM-day
Na_2CO_3:	147 lb/M ACFM-day
Labor:	Fixed at 1½ men/shift (With 20% allowance for fringes and benefits)
Maintenance:	0.06 C.I.
Capital Charges:	15 year life Taxes, insurance, etc. 2.5% C.I.

USER INPUTS

(ACFM)	=	Effluent gas flow rate
(Days)	=	Annual days of operation
*($/kWh)	=	Electric power
*($/M gal)	=	Raw water
*($/M gal)	=	Condensate
*($/M lb)	=	Steam
*($/lb)	=	H_2SO_4
*($/lb)	=	Na_2CO_3
*($/hr)	=	Labor
($/ton liquid SO_2 credit (if taken)	=	
(i)	=	Interest rate
*($/lb)	=	DMA.

*See appendix II for mid-1974 costs.

CAPITAL, OPERATING AND ANNUALIZED CAPITAL COST EQUATIONS

036 DOUBLE ALKALI PROCESS (SO_2 RECOVERY 90%)

(Single scrubber only - no separate particulate scrubbing)

Maximum Sized System: 350,000 ACFM

CAPITAL COST (C.I.) $= 1000\ (ACFM)^{0.60} + 200{,}000(E)^{0.65}$

where,

(ACFM) = effluent gas flow rate
(E) = SO_2 emission rate tons/day

ANNUAL OPERATING COST $AOC = \left(\frac{ACFM}{1000}\right)(Days)\left[240(\$/kWh) + 1.5^{*}(\$/MM\ Btu)\right]$

$+ (E)(Days)\left[190(\$/kWh) + 1.9(\$/M\ gal\ H_2O) + 1.14\ (\$/ton\ CaO)\right.$

$\left. + 0.19(\$/ton\ Na_2CO_3)\right] + 21{,}024(\$/hr) + 0.06(C.I.) + 3.33(\$/ton\ sludge) + 0.025\ (C.I.)$

*Utility applications only.

TOTAL ANNUAL CHARGES $TAC = \left[\frac{i(1+i)^N}{(1+i)^N - 1}\right](C.I.) + (AOC)(1-\theta) - \left[\frac{2(C.I.)}{N}\left(\frac{N}{N+1}\right)\right]\theta$

where,
θ = taxation rate $0 < \theta < 1$
i = interest rate
N = life of equipment

ANNUAL SLUDGE PRODUCTION $= 3.2(E)(Days)$

NOTE: Annual operating cost includes sludge disposal.

OPERATING DATA INPUT

Power:	Scrubbing 0.24 kWh/ACFM-day
Reheat:	0.0015 MM Btu/ACFM-day(utility applications only)
Water:	4 M gal/ton sulfur
Lime(CaO):	2.4 tons/ton sulfur
Soda ash (Na_2CO_3):	0.4 tons/ton sulfur
Labor:	Fixed at 2 men/shift (with 20% allowance for fringes and benefits)
Maintenance:	0.06 C.I.
Capital Charges:	15 year life Taxes, insurance, etc. 2.5% C.I.

USER INPUTS

(ACFM)	=	Effluent gas flow rate
(E)	=	SO_2 emission rate tons/day
(Days)	=	Annual days of operation
*($/kWh)	=	Electric power
*($/M gal)	=	Raw water
*($/MM Btu)	=	Reheat (for utility applications)
*($/ton)	=	Lime (CaO)
*($/ton)	=	Soda ash (Na_2CO_3)
($/hr)	=	Labor rate
($/ton)	=	Cost of disposal of sludge solids
(i)	=	Interest rate

*See appendix II for Mid-1974 costs.

CAPITAL, OPERATING AND ANNUALIZED CAPITAL COST EQUATIONS

037 CITRATE PROCESS (SO_2 RECOVERY 95%)

(Includes particulate scrubbing)

Maximum Sized System: 350,000 ACFM

$$\text{CAPITAL COST (C.I.)} = 1800(\text{ACFM})^{0.60} + 220{,}000(\text{E})^{0.60}$$

where,

(ACFM) = effluent gas flow rate
(E) = SO_2 emission rate tons/day

$$\text{ANNUAL OPERATING COST AOC} = \left(\frac{\text{ACFM}}{1000}\right)(\text{Days})\left[300(\$/\text{kWh}) + 1.5^{*}(\$/\text{MM Btu})\right]$$

$$+ (\text{E})(\text{Days})\left[190(\$/\text{kWh}) + 1.71(\$/\text{M gal } H_2O) + 3.8\ (\$/\text{M lb steam})\right.$$

$$\left. + 6.37(\$/\text{MCF methane}) + 4.28(\$/\text{lb citric acid}) + 29.2(\$/\text{lb } Na_2CO_3)\right]$$

$$+ 26{,}280(\$/\text{hr}) + 0.06(\text{C.I.}) + 0.025(\text{C.I.})$$

*Utility applications only.

$$\text{TOTAL ANNUAL CHARGES TAC} = \left[\frac{i(1+i)^N}{(1+i)^N - 1}\right](\text{C.I.}) + (\text{AOC})(1-\theta) - \left[\frac{2(\text{C.I.})}{N}\left(\frac{N}{N+1}\right)\right]\theta$$

where,

θ = taxation rate $0<\theta<1$
i = interest rate
N = life of equipment

ANNUAL SULFUR PRODUCTION CREDIT OR DEBIT = (0.475E)(Days)$/ton)

OPERATING DATA INPUT

Power:	Scrubbing 0.30 kWh/ACFM-day
	Sulfur Handling 400 kWh/ton sulfur
Reheat:	0.0015 MM Btu/ACFM-day (utility applications only)
Process Water:	3.6 M gal/ton sulfur
Steam:	8 M lb/ton sulfur
Methane:	13.4 M CF/ton sulfur
Citric Acid:	9 lb/ton sulfur
Soda Ash:	61.5 lb/ton sulfur
Labor:	Fixed at 2½ men/shift (with 20% allowance for fringes and benefits)
Maintenance:	0.06 C.I.
Capital Charges:	15-year life Taxes, insurance, etc. 2.5% C.I.

USER INPUTS

(ACFM)	=	Effluent gas flow rate
(E)	=	SO_2 emission rate-tons/day
(Days)	=	Annual days of operation
*($/kWh)	=	Electric power
*($/ MM Btu)	=	Reheat (for utility applications)
*($/ M gal)	=	Process water
*($/ M lb)	=	Steam
*($/lb)	=	Citric acid
*($/lb)	=	Soda ash (Na_2CO_3)
($/hr)	=	Labor rate
($/ton)	=	Credit or debit for elemental sulfur disposal
(i)	=	Interest rate

*See appendix II for mid-1974 costs.

CAPITAL AND TOTAL ANNUALIZED COST EQUATIONS

GAS CLEANING AND CONDITIONING

Applied to SO_2 containing effluent streams if

a) temperature >130°F , and /or

b) particulates >0.01 gr/SCF unless otherwise noted

$$\text{CAPITAL COST (C.I.)} = 750\left(\text{ACFM} \times \frac{520}{460 + T}\right)^{0.68}$$

where,

ACFM = effluent gas flow to conditioning plant

T = temperature of gas (°F) to conditioning plant

$$\text{ANNUAL OPERATING COST AOC} = (\text{Days})\left(\frac{\text{ACFM}}{1000} \times \frac{520}{(460 + T)}\right)\left[245(\$/\text{KWH}) + 13(\$/\text{M gal})\right]$$

$$+5{,}256(\$/\text{hr}) + 0.06(\text{C.I.}) + 0.025(\text{C.I.})$$

where,

(Days) = Annual days of operation

TOTAL ANNUAL CHARGES

$$TAC = \left[\frac{i(1+i)^N}{(1+i)^{N-1}}\right](C.I.) + (AOC)(1-\theta) - \left[\frac{2(C.I.)}{N} \cdot \frac{N}{N+1}\right]\theta$$

where

θ = taxation rate $0<\theta<1$
i = interest rate
N = life of equipment

FLOW RATE OF CONDITIONED EFFLUENT STREAM

$$ACFM' = \left(\frac{ACFM}{460 + T}\right)(552.4 + 0.289T)$$

where,

ACFM = gas flow rate to conditioning plant

T = temperature (°F) of effluent stream to conditioning plant

Temperature of Conditioned Effluent Stream = 130°F

OPERATING DATA INPUT

Power:	245kWh/M SCFM-day
Raw Water:	13 M gal/M SCFM-day
Labor:	Fixed at ½ man/day (With 20% allowance for fringes and benefits)
Maintenance:	0.06(C.I.)
Capital Charges:	15-year life taxes, insurance, etc. 2.5%C.I.

USER INPUTS

(Days)	=	Annual days of operation
(ACFM)	=	Effluent gas flow to gas conditioning
(T°)	=	Temperature (°F) of effluent gas to gas conditioning
*($/kWh)	=	Electric power
*($/M gal)	=	Raw water
($/hr)	=	Labor rate
(i)	=	Interest rate

*See appendix II for mid-1974 costs.

8.0 CONVERSION OF OIL- OR GAS-FIRED BOILERS TO COAL-FIRED

The factors which may affect the conversion of an oil or gas-fired boiler to a coal-fired unit are many and varied, and a generalized approach can only be approximate. Packaged boilers, for instance, cannot be converted while the larger radiation areas needed for coal combustion make other boiler type conversions difficult and often impractical to undertake.

For the purposes of this study, it has been assumed that conversion can be achieved only by replacement of the oil- or gas-fired boiler with a new coal-fired unit. Costs will thus include removal of the original boiler, retrofitting the new boiler to the existing structure and generating equipment and provision of coal handling facilities.

On the basis of a conversation with a representative of Babcock and Wilcox, a cost of $10/lb steam or $85/kW has been taken as a representative cost of a coal-fired boiler including pulverizers, up to 200 MW in size. The 1970 National Power Survey provides estimated average investment cost for new generating capacity at 1968 price levels as follows:

<100 MW	$203/kW	=	$288/kW (1974 costs)
100 - 300 MW	$188/kW	=	$267/kW (1974 costs)

Boiler cost might reasonably be expected to account for approximately one-third of the total utility costs and the base cost of $85/kW falls within this range.

Two main parameters affecting boiler costs appear to be lbs/steam generated and the steam pressure. However, since the NEDS file reports rated boiler capacities in MM Btu/hr and does not report on steam pressure, the cost equation has been developed only on the basis of MM Btu/hr. A retrofitting factor of 1.5 has been used.

Coal handling costs have been developed from data included in "Systems Evaluation of Refuse as a Low Sulfur Fuel," Vol. II, Envirogenics Company, Nov. 1971, PB-209-272, and are based on MM Btu/hr.

No equation for operating costs has been developed. It is assumed that operating costs apart from fuel costs will be the same as for the original boiler. Fuel costs will be computed from the existing routines in the Implementation Planning Program.

CAPITAL COST EQUATION

024, 025, 026 CONVERSION OF OIL- OR GAS-FIRED BOILER

$$\text{CAPITAL COST(c.i.)} = 41{,}650(\text{MM Btu/hr})^{0.80} + 4{,}390(\text{MM Btu/hr})^{0.74}$$

where,

MM Btu/hr = rated capacity of boiler in million Btu/hr

9.0 REFERENCES

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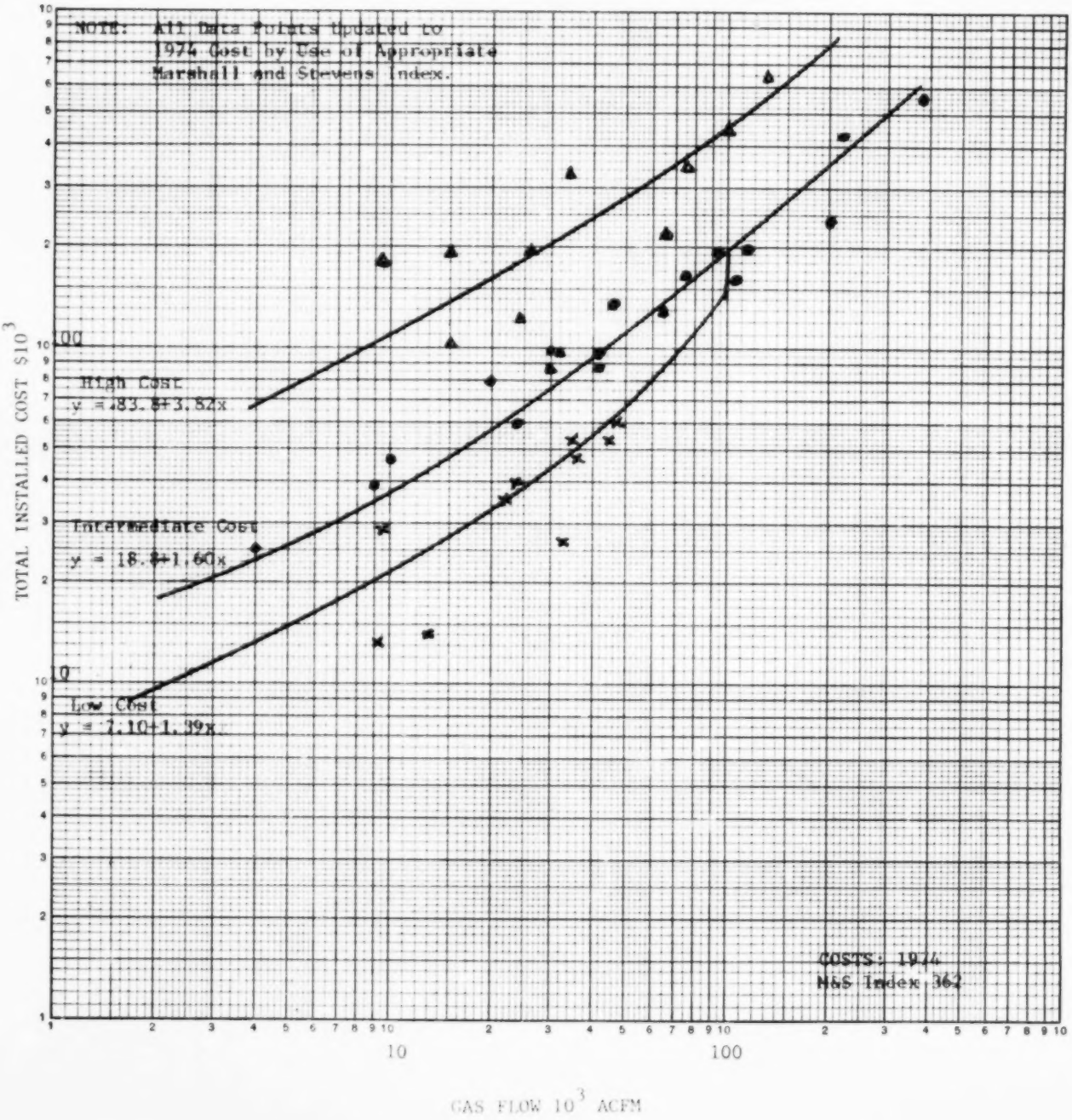
APPENDIX I

		Page
Chart 1 -	Installed Capital Cost Wet Scrubbers	132
2 -	Installed Capital Cost - Cyclones	133
3 -	Installed Capital Cost - Electrostatic Precipitators	134
4 -	Installed Capital Cost - Mist Eliminators	135
5 -	Installed Capital Cost - Fabric Filters	136
6 -	Installed Capital Cost - Afterburners	137

APPENDIX I Chart 1

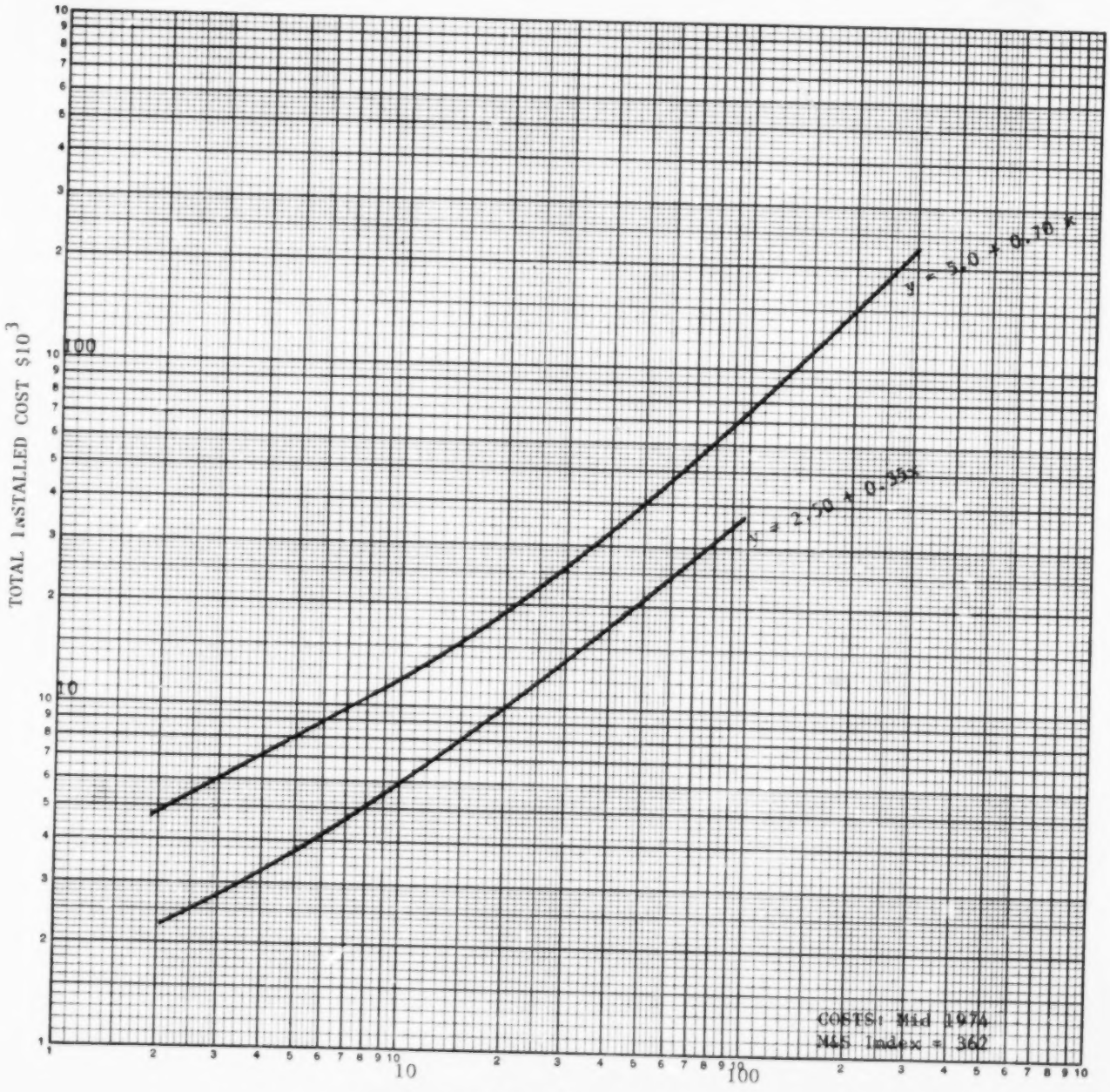
INSTALLED CAPITAL COST WET SCRUBBERS



APPENDIX I

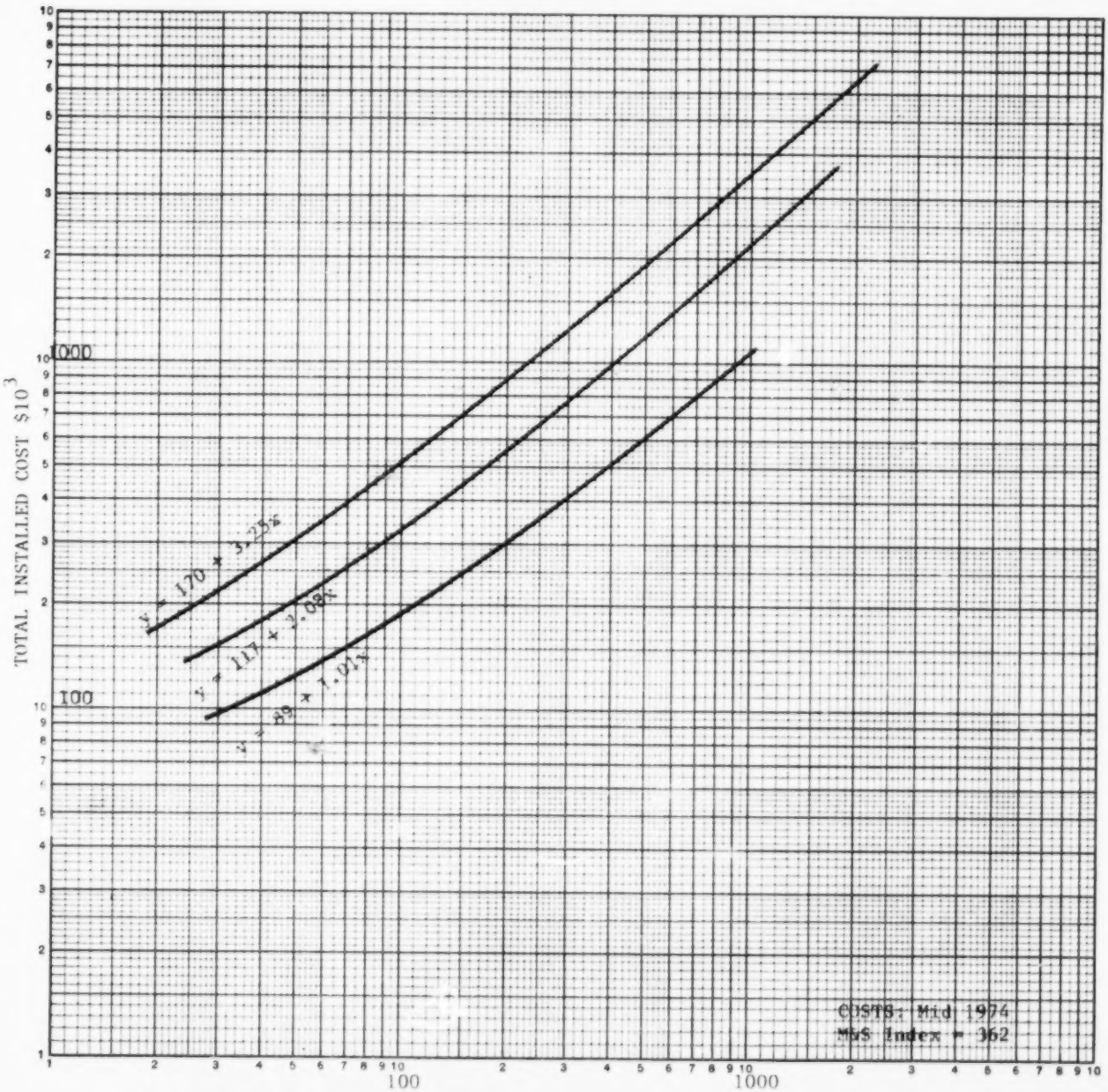
Chart 2

INSTALLED CAPITAL COST - CYCLONES



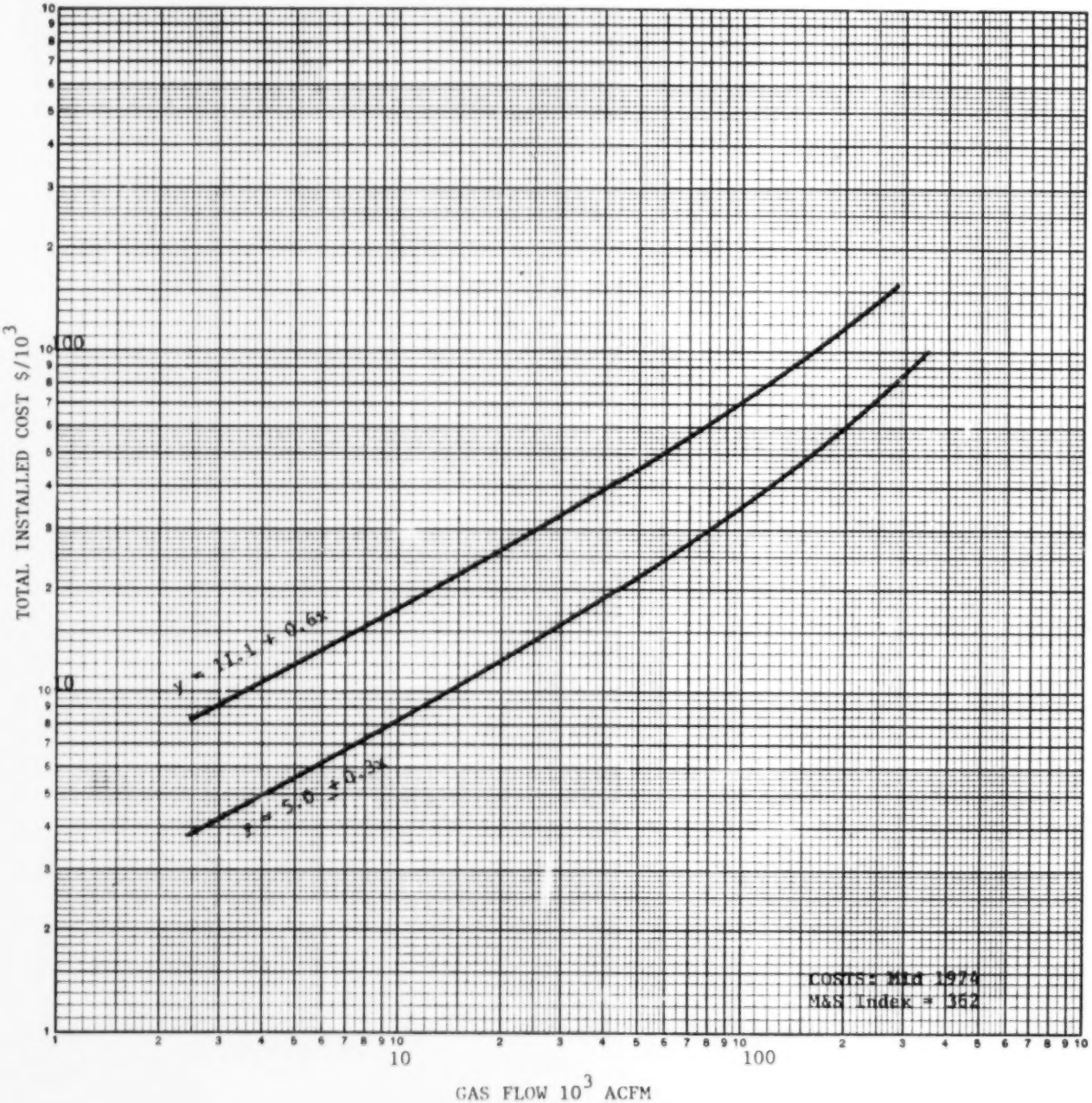
APPENDIX I Chart 3

INSTALLED CAPITAL COST - ELECTROSTATIC PRECIPITATORS



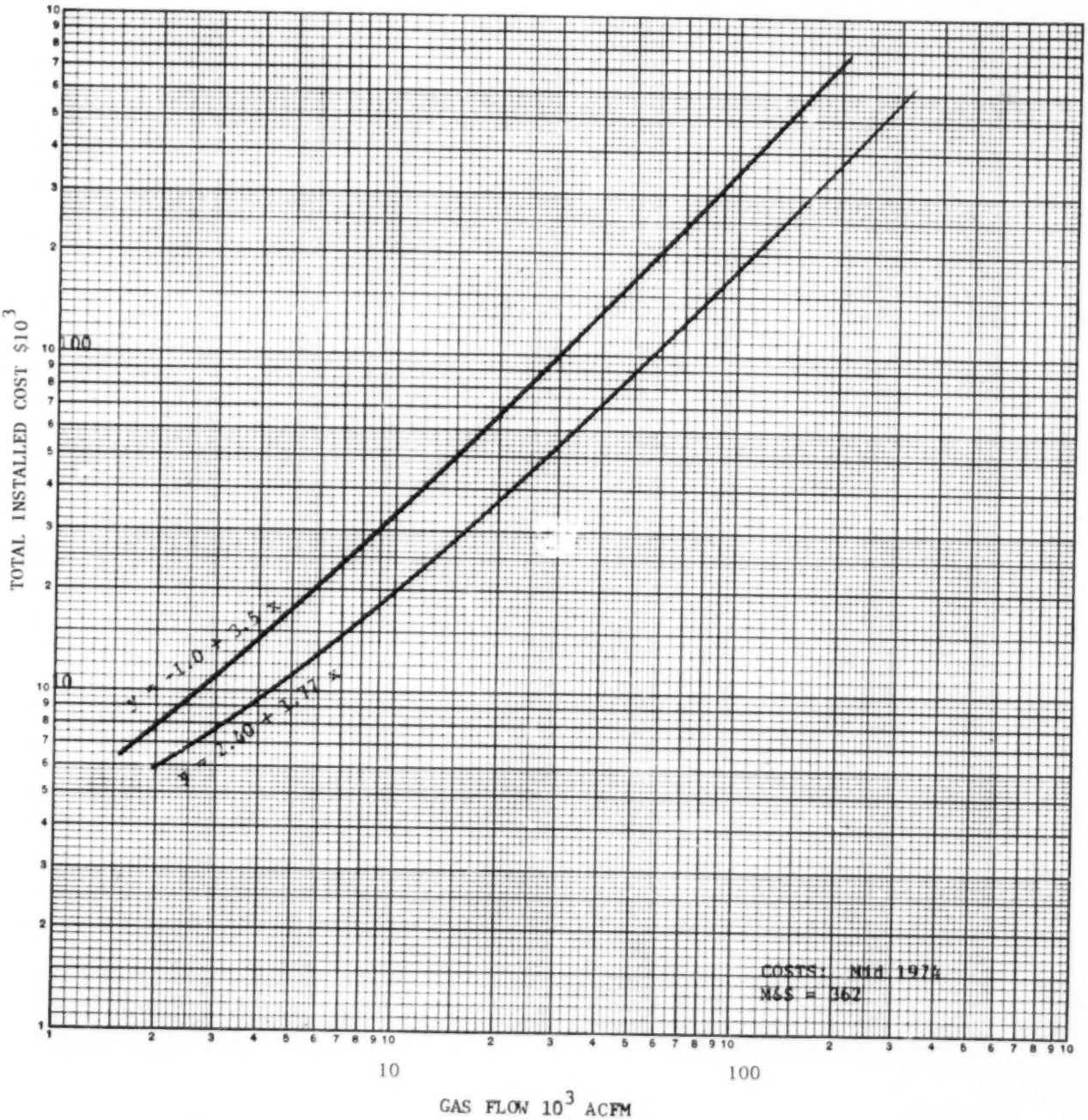
APPENDIX I Chart 4

INSTALLED CAPITAL COST - MIST ELIMINATORS



APPENDIX I Chart 5

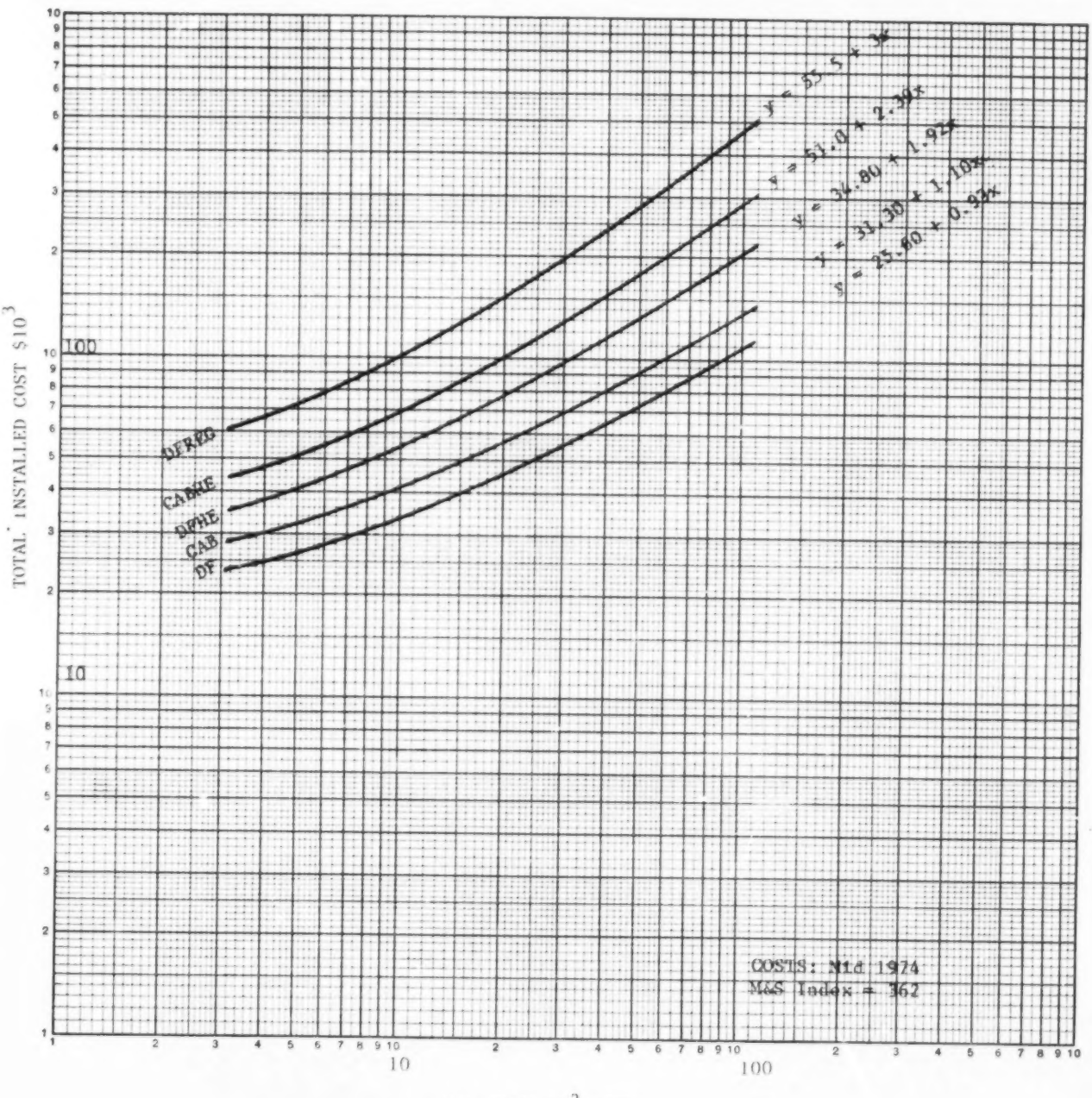
INSTALLED CAPITAL COST - FABRIC FILTERS



APPENDIX I

Chart 6

INSTALLED CAPITAL COST - AFTERBURNERS



APPENDIX II

CHEMICAL AND UTILITY UNIT COSTS FOR DESULFURIZATION PROCESSES
As of Mid-1974

A. Chemicals	Costs
Limestone ($CaCO_3$)	$8/ton
Soda ash (Na_2CO_3)	$50/ton
Lime (CaO)	$22/ton
Citric acid	42.5¢/lb
Dimethylaniline (DMA)	35.0¢/lb
Sulfuric acid (98%)	$45/ton
Methane	$1.25/M CF
Catalyst (Alumina oxide)	16¢/lb
B. Utilities	
Electric Power	$0.0150/kWh
Steam	$1.25/M lb
Heat	$1.25/MM Btu
Cooling Water	$0.10/M gal
Process Water	$0.30/M gal
Condensate	$0.05/M gal
Natural Gas	$1.25/M CF

Sources: 1) Chemical costs have been taken from the Chemical Marketing Reporter published weekly by the Schnell Publishing Co., Inc. Adjustments have been made where necessary to allow for bulk quantities.

2) Utility costs have been established on the basis of discussions with representatives of engineering companies.